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14. ABSTRACT

The objective of this research is to increase current understanding of drylands hydrology by quantifying the hydrologic response of two geomorphic surfaces in an ephemeral wash to seasonal precipitation inputs. Specifically, the aim is to understand how water is partitioned in space and time across these geomorphic surfaces, and the associated soil and vegetative response to seasonal precipitation. The physiogeographic region of study is Yuma Wash, a hyperarid watershed located in the Lower Colorado River Valley region of the Sonoran desert in the

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Quantifying the Complex Hydrologic Response of a Desert Ephemeral Wash

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Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT SUPPORTED
Susan Howe	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT SUPPORTED	National Academy Member
Jorge A Ramirez	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED
FTE Equivalent:	
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Names of Personnel receiving masters degrees

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NAME

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Names of other research staff

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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

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Technology Transfer

Quantifying the Complex Hydrologic Response of a Desert Ephemeral Wash

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Statement of Research

The objective of this research is to increase current understanding of drylands hydrology by quantifying the hydrologic response of two geomorphic surfaces in an ephemeral wash to seasonal precipitation inputs. Specifically, the aim is to understand how water is partitioned in space and time across these geomorphic surfaces, and the associated soil and vegetative response to seasonal precipitation. The physiogeographic region of study is Yuma Wash, a hyperarid watershed located in the Lower Colorado River Valley region of the Sonoran desert in the southwestern United States (Figure 1). Yuma Wash drains an area of approximately 186 km^2 and is politically bound within the United States Army Yuma Proving Ground (YPG), the primary Department of Defense (DoD) desert environmental test center, which spans approximately 3390 km^2 of the Sonoran Desert (Figure 2). The approach was field-based, using state of the science instrumentation to quantify several hydrologic components over a four year period, the details of which are outlined below.

Research relevance

The establishment of a well-instrumented watershed on Department of Defense (DoD) lands in an arid environment provides data necessary for military and management personnel to improve military terrain analyses, and to practice effective stewardship on the lands they manage and train on. The dynamic and highly variable nature of arid lands hydrology coupled with extreme climatic seasonality pose particular challenges to Army operations. Seasonal fluxes of energy and water influence human and material performance, maneuverability and trafficability on the landscape, and remote sensing detection of subsurface terrain properties, including landmines and unexploded ordnance (U.S. Army Research Office, 2006). Hydrological and other physical and biological data across varying geomorphic terrain are needed to better understand, simulate, and predict environmental conditions that are most restrictive to these and other operational performance.

Just as terrain properties impose physical and biological constraints on military operations, military activities in turn impose impacts on terrain properties. Resiliency of terrain to perturbation depends on a complex set of interactive variables, which broadly include the type, degree, and extent of disturbance in space and time, and whether landscape properties and processes critical to maintain system function have been irreparably disrupted. In order to effectively manage military lands without compromising either the mission of the respective military installation, or the ecological integrity of DoD lands or the larger landscape for which other federal and state organizations are responsible, a greater scientific effort to understand natural and human-altered process-relationships in arid lands is required. Since water availability drives (and constrains) the establishment and maintenance of many properties and processes in arid environments, it follows that ecological system function is inextricably tied to the seasonal partitioning of water across the physical and biological landscape. Quantifying these fluxes is therefore a logical first step toward elucidating those elements necessary to support and maintain the ecological integrity of DoD lands in arid environments.

In addition to the direct benefits these data will provide to DoD, quantifying the hydrologic response in arid regions is important for at least three reasons:

(i) Arid and hyperarid regions exhibit unique rainfall and runoff characteristics that are not widely documented, and are unique hydrologically in several aspects. Annual precipitation rarely exceeds 250 mm, and multiple years in which rainfall is considerably less are common. Yet a single storm event can deliver the entire annual allotment of precipitation over a period of hours. Convective precipitation, driven in part by seasonal differential heating of desert floors, can cause intense, localized flash flooding, yet most streams are dry the majority of the year. Pulsed rainfall events such as these result in highly dynamic and non-linear eco-hydrologic responses, in part because of the partial area coverage of these storms (Goodrich *et al.*, 1997), but also because of marked differences in surface and subsurface features common in desert landscapes.

(ii) The relationship between vegetation, soils, and geomorphology influences seasonal water partitioning in arid landscapes. Water is the principal limiting factor for the biotic environment of desert ecosystems, and the extent to which plants can access this resource depends in large part on the characteristic precipitation they receive, the soil characteristics at and beneath the surfaces on which they establish, and the adaptive strategies employed by each species. Pedogenic processes are time-dependent and vary across different geomorphic landforms. The development of argillic or petrocalcic horizons in alluvial fan deposits is reflective of older desert soils, and these features have a significant influence on soil hydrology. By restricting soil permeability, they retard infiltration and often define the vertical extent of rooting zones of many plants. This results in the lateral extension of root systems that can then accelerate subsurface flow through the development of pipes and macropores (Hamerlynck *et al.*, 2002). Soil profiles above these indurated horizons may hold significant moisture following a rainfall event. However, it is likely that these profiles also experience a higher degree of seasonal amplitude in moisture availability than do younger soils beneath active fluvial surfaces. Differences in soil hydrology on alluvial fan surfaces in deserts have also been attributed to down-gradient fining, where coarser soils on upper fan surfaces have been associated with higher infiltration rates and a greater diversity of plants, and finer soils on lower fan surfaces have been correlated with higher surface runoff rates, increased evaporation, concentration of salts through capillary action, and lower vegetation diversity (Phillips *et al.*, 1978; Yang and Lowe, 1956; Bowers and Lowe, 1986; Key *et al.*, 1984). However, other studies suggest the relationship between soil properties, vegetative communities, and fan position is not straightforward and is more significantly related to properties such as depth to an impermeable horizon, and the presence or absence of desert pavement surfaces (Smith *et al.*, 1997). These studies highlight the complex relationship between plant community structure, pedogenic development, and the geomorphic history of a basin that influences water partitioning in arid deserts. To date, these interactions have only received cursory attention.

(iii) Conventional water balance methods do not provide accurate estimates of hydrologic response in arid and hyperarid environments. There are several reasons for this. First, highly variable precipitation coupled with the sparse network of meteorological stations in most arid and hyperarid regions constrain the accuracy of rainfall estimates. Second, poor documentation of highly localized, ephemeral runoff characterized by high rates of transmission loss constrains regional estimates of streamflow and groundwater recharge. Third, estimates of potential evapotranspiration (ET_p) often used to estimate evaporative losses typically exceed actual evapotranspiration (ET_a) in such water-limited systems by an order of magnitude or more, so that even small errors in estimates can result in large discrepancies in overall water balances. Documentation of the seasonal and spatial characteristics of precipitation, soil moisture response,

and evaporative losses across variable terrain provides an opportunity to improve water balance estimates for arid and hyperarid regions.

As a relatively undisturbed site located within the boundaries of the Yuma Proving Grounds, Yuma Wash provides a unique setting for establishing baseline hydrologic, geomorphic, and vegetative conditions required for arid and hyperarid lands management. In 1995, Ayres Associates was tasked with inventorying the biophysical landscape of Yuma Wash. While this initial effort provided valuable information on soils, geomorphology, and vegetative communities present in the Wash (Ayres Associates, 1996), there remained a pressing need to understand process relationships among these resources and, in particular, the linkages between seasonal precipitation, soil moisture, and plant water use. The current research aims at quantifying some of these linkages through the measurement of seasonal precipitation, soil moisture fluxes, and evapotranspiration across two geomorphic surfaces that comprise most of the Yuma Wash watershed. Given recent trends in human population expansion, global and regional climate shifts, and increased concern over water scarcity in these regions, understanding the hydrodynamics of dryland systems is emerging as an important focal area for hydrologic and geomorphic research.

Questions and hypotheses

Four basic research questions were addressed to understand how water is partitioned in space and time over two distinct geomorphic surfaces and their associated soils and vegetative communities in the Yuma Wash watershed in response to seasonal precipitation:

- *Question 1:* What are the seasonal storm characteristics in Yuma Wash? Specifically, how does the amount and rate of rainfall vary in time and space? Does geographic position in the watershed or geomorphic surface influence total rainfall or the rate of rainfall received?
- *Question 2:* How do soil moisture fluxes vary across two geomorphic surfaces in response to seasonal precipitation? Specifically, do young alluvial wash soils respond differently to seasonal precipitation than intermediate relict alluvial terrace soils?
- *Question 3:* How do two woody plant species (*Parkinsonia microphylla* and *Olneya tesota*) found on each of these geomorphic surfaces respond to seasonal precipitation and subsequent soil moisture availability?
- *Question 4:* How does evapotranspiration vary in response to seasonal precipitation across these geomorphic surfaces, and how do direct measurements of actual evapotranspiration (ET_a) by eddy covariance methods compare against indirect estimates of potential evapotranspiration (ET_p) from physically based equations, and against direct measurements of evaporation (ET_{pan}) from pan evaporimeters?

Several working hypotheses integrating these components of the hydrologic response were postulated as a framework for addressing the research questions:

- *Hypothesis 1*: Inter-annual variability in the amount and rate of precipitation is likely high between all years, and intra-annual variability is likely high between all seasons.
- *Hypothesis 2:* Spatial variation in precipitation is high, particularly during summer months, and influenced more by proximity of stations than geomorphic surface.
- *Hypothesis 3:* Frontal storms bringing long-duration, low-intensity precipitation during cooler winter months likely result in deeper and more persistent soil moisture on

intermediate terrace surfaces than soil moisture resulting from summer convective storms.

- *Hypothesis 4:* Convective storms bringing short-duration, high-intensity, localized precipitation likely result in greater infiltration beneath Young alluvial wash surfaces than Intermediate terrace surfaces.
- *Hypothesis 5: Parkinsonia microphylla* and *Olneya tesota* growing in young alluvial washes are less hydrologically responsive to seasonal precipitation (measured as sapflux) than in the same species growing on intermediate relict terraces.
- *Hypothesis 6*: Sapflux in *Parkinsonia microphylla* and *Olneya tesota* is likely higher during summer months than winter.
- *Hypothesis 7:* Direct measurements of actual evapotranspiration (ET_a) via eddy covariance techniques, and estimates of potential evapotranspiration (ET_p) from meteorological measurements using the Penman-Monteith equation, are greater over young alluvial washes than intermediate relict terrace surfaces, and are highest over both surfaces following summer convective storms.

Materials and methods

Data were gathered and analyzed from a suite of hydrometeorological instrumentation deployed throughout Yuma Wash on two geomorphic surfaces—the active alluvial wash and relict alluvial terrace (Figure 3 and Plate 1). Data acquisition commenced in July, 2006 and instrumentation was operational through February, 2010. Six fully instrumented meteorological stations (Campbell Scientific, Inc.) provided data on precipitation, near surface soil moisture and heat flux, and a suite of additional variables required to estimate evapotranspiration (as ET_p) via the Penman-Monteith equation (Plate 2). Two of the stations were additionally equipped with sonic anemometers and water vapor analyzers (CSAT; Campbell Scientific, Inc. and LI7500; LiCor Biosciences) for direct measurement of actual evapotranspiration (ET_a) via eddy covariance techniques (Plate 3). All meteorological instrumentation was installed at approximately 2 m above the ground surface, with the exception of the instrumentation at station ECOV2. For the purposes of computing fluxes of water vapor over alluvial wash surfaces, sensors were mounted approximately 2 m above the mean vegetative canopy height (approximately 7.5 m from the ground surface). Since relict alluvial terraces in Yuma Wash are comprised predominantly of desert pavement surfaces with less than 5% vegetation cover, water vapor flux sensors were installed with other meteorological instrumentation at 2 m above the ground surface. Tipping-bucket rain-gages (TE525 and TB4; Campbell Scientific, Inc.) were programmed to be event-triggered and measure total rainfall at 5-minute and 15-minute intervals. All other meteorological variables were measured at 60-second intervals, which were averaged and outputted every 15 minutes. Stations equipped with eddy covariance sensors recorded concentrations of water vapor at 10Hz, along with wind speed, air temperature, and humidity, which were then used to compute vertical fluxes of sensible and latent heat. Fluxes were computed, averaged and outputted every 30 minutes. All eddy covariance raw time series data were despiked, planar-fit coordinate rotated, spectrally corrected (Lee *et al.*, 2004), time lag adjusted (Horst, 2008), and WPL corrected (Webb *et al.*, 1980) for changes in atmospheric density of the covariances.

A single soil moisture sensor, four soil temperature sensors (CS616 and TCAV; Campbell Scientific, Inc.), and two heat flux plates (Hukeflux) were emplaced beneath the soil surface at 2.5, 4, 6, and 8 cm, respectively, at each meteorological station (Plate 4). Collectively these data were used to compute the soil storage term, G, and coupled with measurements of net radiation, sensible and latent heat to examine the energy balance for Yuma Wash. Soil moisture at depths of 25, 50, and 100 cm, and tree sapflux were measured at 6 stations placed in proximity to each meteorological station (Plate 5). Soil samples were collected at depths of 2.5, 4, 25, 50, and 100 cm at each site, and 60 soil water content reflectometers were laboratory-calibrated for moisture content to each soil type prior to installation. In addition to the single soil moisture sensor installed at 2.5-4 cm at each of the 6 meteorological stations, 9 sensors were installed at each sapflux/soil moisture station at depths of 25, 50, and 100 cm; 3 beneath bare ground, and 3 each within the dripline radius of *Parkinsonia microphylla* and *Olneya tesota* (Plate 6). Soil temperature sensors (T107, Campbell Scientific, Inc.) were installed beside each soil moisture probe thus allowing moisture readings to be corrected for temperature fluxes, a variable known to introduce measurement error in the particular soil moisture probe deployed.

A total of 36, 3-needle sapflow sensors (East30 Sensors, Inc.) were installed in the sapwood of *Parkinsonia microphylla* and *Olneya tesota* (3 sensors per tree; 2 trees per station) (Plate 7). These two species were selected for measuring sapflux and subsurface soil moisture because they are ubiquitous in Yuma Wash, and are found on both geomorphic surfaces under study, thus allowing relative measures of water use to be made in the same species across varying geomorphic terrain.

To provide a third estimate of evaporative loss (as pan evapotranspiration, ET_{pan}), 2 National Weather Service Class A pan evaporimeters (NovaLynx, Inc.) were installed on each of the geomorphic surfaces under study (Plate 8), and programmed to record hourly changes in water level, which were assumed to be losses to evaporation. Pans were equipped with automatic refill systems, and data were corrected for increases in water level during timed refill intervals (every 72 hours at 0300 hours) and following precipitation events. Pans required a mesh screen cover to avoid water consumption by wildlife (Plate 8 inset). Attempts were made to calibrate the pan for reduction in evaporative losses due to the pan cover, but continual use of the adjacent uncovered pan by wildlife rendered this procedure infeasible in this setting. Published correction values range from 10 per cent (Howell *et al.*, 1983), 12.8 per cent (Campbell and Phene, 1976), to 20 per cent (FAO, 2010), and for the purposes of this research, a 15% correction coefficient was used, which was based on data collected prior to covering of pans.

Precipitation recorded at the six meteorological stations was analyzed on an event, seasonal, and annual basis. In general, precipitation data from all stations were found to be non-normally distributed and left skewed. Therefore non-parametric methods were employed to determine statistical significance in space and time, and compared against parametric tests where appropriate (see Appendix B for statistical output). Soil moisture, tree sapflux, and evapotranspiration data are still currently being analyzed in response to specific precipitation events, and statistical differences in space/time domains are also being evaluated. Because several unforeseen events have resulted in delays in completion of the data analysis, information provided in this final report therefore reflects only the analysis conducted to date. However, data analysis is continuing and an expanded report will be produced later in 2011.

Findings

Findings are presented below as they relate to each of the four research questions and associated hypotheses. Non-statistical data are presented in Tables embedded within the text, Figures and Plates are provided in Appendix A, and statistical output is provided in Appendix B.

- *Question 1:* What are the seasonal storm characteristics in Yuma Wash? Specifically, how does the amount and rate of rainfall vary in time and space? Does geographic position in the watershed or geomorphic surface influence total rainfall or the rate of rainfall received?

Total and mean annual precipitation recorded at six stations in Yuma Wash, and at the Yuma Proving Grounds station (YPG/DCP1) from July 2006 to February 2010 are presented in Table 1 and Figure 4. While there is clearly some spatial variation in precipitation recorded throughout Yuma Wash, statistical differences ($\alpha = 0.05$) in the distribution of seasonal and annual precipitation between each of the six stations were not found (Appendix B). Temporal (inter- and intra-annual) variation in precipitation was in general greater than spatial variation in Yuma Wash for the period of record, and statistical differences were found between most seasons and most years (Appendix B). When data are summarized by season, inter-annual variation is pronounced for all seasons except summer (Table 2; Figure 5; Appendix B).

Table 1. Annual precipitation recorded and averaged from six stations in Yuma Wash.

Station	**Precipitation** (mm)				
	2006*	**2007**	**2008**	**2009**	**2010***
ECOV1/ECOV1R	29	23	106	40	83
ECOV2**	--	92	121	40	96
MET1**	10	79	105	50	96
MET2	69	68	106	44	102
MET3	67	81	160	47	101
MET4	62	73	147	54	100
MAP	59	78	125	51	100
YPG/DCP1	43	29	89	66	116

MAP refers to mean annual precipitation averaged across all stations where records were complete for the year. * Data were collected from July 2006 to February 2010, therefore precipitation values for 2006 and 2010 are partial year-totals. **MET1 data were missing from July-September 2006 due to station malfunction, and ECOV2 station was not operative in 2006; therefore neither of these stations were included in the 2006 MAP estimate.

Table 2. Seasonal precipitation averaged from six stations in Yuma Wash for the period of record, compared against longer term seasonal averages recorded at the Yuma Proving Grounds meteorological station from 1958-2010.

Year	**Winter** (mm)	**Spring** (mm)	**Summer** (mm)	**Fall** (mm)
2006 (winter 05-06)	N/A	N/A	46	13
2007 (winter 06-07)	2	1	39	37
2008 (winter 07-08)	21	10	43	32
2009 (winter 08-09)	38	0	28	0
2010 (winter 09-10)	104	N/A	N/A	N/A
Yuma Wash mean 2006-10	41	4	39	20
YPG/DCP1 mean 1958-10	44	5	31	14

The bimodal pattern typical of Southwest precipitation is also apparent in these data, where rainfall is received primarily in winter and summer months with occasional fall events. Summer precipitation tends to be more consistent in time than precipitation received in other seasons, a trend recognized in other areas of the Southwest. With the exception of winter precipitation recorded in Yuma Wash during 2006-07, winter precipitation for the period of record roughly correlates (positively) with changes in sea surface temperature (SST) values as expressed by the Oceanic Nino Index (ONI) in the Niño 3.4 region, which signal ENSO anomalies (Table 3; Figure 6). El Niño and La Niña episodes during the period of record are reflected in Table 3, and are defined as 5 consecutive overlapping periods where 3-month running mean SST values exceed +/- 0. 5^{o}C for the Niño 3.4 region.

Table 3. Historical Pacific warm (RED) El Niño and cold (BLUE) La Niña episodes for the period of record based on a threshold of +/- 0.5 ^{o} C for Oceanic Nino Index (ONI). (Source: NOAA/CPC, 2010)

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2005	0.7	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.2	-0.1	-0.4	-0.7
2006	-0.7	-0.6	-0.4	-0.1	0.1	0.2	0.3	0.5	0.6	0.9	1.1	1.1
2007	0.8	0.4	0.1	-0.1	-0.1	-0.1	-0.1	-0.4	-0.7	-1.0	-1.1	-1.3
2008	-1.4	-1.4	-1.1	-0.8	-0.6	-0.4	-0.1	0.0	0.0	0.0	-0.3	-0.6
2009	-0.8	-0.7	-0.5	-0.1	0.2	0.6	0.7	0.8	0.9	1.2	1.5	1.8
2010	1.7	1.5	1.2	0.8	0.3	-0.2	-0.6	-1.0				

Spatial analyses of the distribution of total precipitation by event and by season do not suggest a relationship between geomorphic surface and the amount of precipitation received in the Yuma Wash watershed. Spatial correlation of event precipitation totals is high between all pairs of stations and between all stations and the six-station mean ($r^2 = 0.79\text{-}0.99$), and the highest correlations were found between stations in closest geographic proximity ($r^2 > 0.97$), irrespective of geomorphic surface. Proximity of stations appears to be a better indicator of spatially correlated precipitation, but again, spatially significant differences in the amount of event and seasonal precipitation received were not found (Appendix B).

Precipitation intensity also varied more in time than space, a characteristic that is pronounced particularly when data are summarized by season (Figure 7). Highest intensity events generally occur in Yuma Wash during summer months and occasionally in the fall, and winter and spring storm intensities vary but are in general considerably less than the rate of precipitation received during summer and fall. Relative to total event precipitation, correlation of mean and maximum event intensities is moderate to high between stations in closest geographic proximity ($r^2_{mean} > 0.59\text{-}0.98$; $r^2_{max} > 0.86\text{-}0.93$), but considerably lower between stations further apart ($r^2_{mean} > 0.01\text{-}0.73$; $r^2_{max} = 0.31\text{-}0.86$). However, MET1 and MET3 were the only stations found to have statistically significant ($\alpha = 0.05$) spatial differences in mean storm intensity (Appendix B). No significant differences were found in maximum storm intensity between any stations, albeit MET1 and MET3 are significant at $\alpha = 0.01$.

In sum, temporal variation in precipitation—both intra- and inter-annual—appears to be greater than spatial variability for the period of record, and data do not suggest a relationship between geomorphic surface and the amount of precipitation received in the Yuma Wash watershed. While variability in precipitation is generally influenced by geographic position in a watershed, statistical differences in the spatial distribution were not found, perhaps due in part to orographic influences affecting the majority of the basin.

- *Question 2:* How do soil moisture fluxes vary across two geomorphic surfaces in response to seasonal precipitation? Specifically, do young alluvial wash soils respond differently to seasonal precipitation than intermediate relict alluvial terrace soils?

Precipitation and volumetric soil moisture response at the near surface (2.5-4cm) are presented for all stations in Figures 8-10a-b. Relict terrace station data are presented in red, and active wash station data in black. Soil moisture data at deeper profiles of 25, 50, and 100 cm are presented for lower basin stations (SF1 on a relict terrace and SF2 in an active wash) in Figures 11-12, and for upper basin stations (SF6 on a relict terrace and SF5 in an active wash) in Figure 13. Statistical analyses of differences in response to moisture inputs across instrumented geomorphic surfaces is still on-going (*i.e.*, timing and magnitude of soil response to a given event, the role of antecedent moisture, and peak attenuation of soil moisture following a storm event), and are therefore not presented here. However, some general trends are apparent. Data analyzed to date suggest that soil moisture does persist longer at the near surface following substantial winter precipitation relative to summer events, on both relict terrace surfaces and active washes, and the quasi-equilibrium state of soil moisture between events is higher during fall and winter events (Figures 8-10b). Soils at all stations are driest at the near surface during spring, and return to these baseline conditions only annually, and in between summer monsoon events given adequate time between events. These seasonal differences at the near surface are likely due to the greater influence of evapotranspiration (when water is available) during spring and summer months. The role of antecedent moisture at the near surface is very apparent across both surfaces and during all seasons. At depths of 25, 50, and 100 cm on relict terraces, soil moisture response to precipitation is greater and more frequent than in active washes, but only in rills and gullies on this surface, where desert pavement and Av horizons have been removed over time, and vegetation and is runoff concentrated, thus allowing for greater infiltration (Figures 11-13). Beneath intact pavement, there is little to no infiltration at depths of 25 cm and greater. In this sense, then, surface runoff is likely more frequently available to plants in gullies on relict terraces than those distributed across interfluves in active alluvial washes, particularly in the lower basin. However, this difference in soil moisture distribution at depth is not as apparent between geomorphic surfaces at the two upper basin stations SF5 and SF6 (Figures 13a-f) as it is at the lower basin stations SF1 and SF2 (Figures 11-12), especially during the wettest period recorded (summer 2008). It is likely that active alluvial channels flow more frequently in the upper basin in response to precipitation than active washes in the lower basin due in part to lesser transmission losses from smaller contributing areas, and possibly orographic effects. So the relationship between seasonal precipitation, soil moisture, geomorphic surface, geographic position, and plant position is complex, and no absolute trends have yet been established. Statistically significant differences and trends will be documented in an expanded report later in 2011.

- *Question 3:* How do two woody plant species (*Parkinsonia microphylla* and *Olneya tesota*) found on each of these geomorphic surfaces respond to seasonal precipitation and subsequent soil moisture availability?

Sapflow data processing is not complete, and we have encountered several technical challenges with the measurements. Therefore limited data are presented here, and a comprehensive documentation of these data will be available in a subsequent final report to be produced later in 2011. A few general trends are worth mentioning at this juncture. As presupposed, both *Parkinsonia microphylla* and *Olneya tesota* species appear to produce their largest sapflux immediately following monsoonal precipitation during summer months, which they receive both as direct precipitation and as concentrated runoff (particularly in gullies on relict terraces where species are concentrated). Both species do respond to winter precipitation, however, but fluxes analyzed to date are considerably less than following summer precipitation.

Vegetation instrumented on upland terraces seem to rely almost exclusively on seasonal precipitation to transport water at rates of >10 cm/hr (measured as sap velocity), whereas the same species in active washes appear to sustain longer periods of sapfow at >10 cm/hr, and depend less on seasonal precipitation inputs to do so. It is therefore plausible that active wash plants rely on larger and less frequent run-off events —perhaps decadal in scale— which result in longer-term storage reservoirs to soil depths greater than we are currently measuring. This type of 'water banking' would allow plants with deep tap and lateral roots systems to draw from a relatively continuous water source during otherwise dry periods, especially for ephemeral wash systems in arid regions given the spatio-temporal variability of precipitation and runoff typical of these environments. To date, however, we have not recorded a decadal-scale precipitation event at any of our sites, and are not measuring soil moisture beyond 1 m in depth. Statistical differences and trends will be included in a forthcoming report later in 2011.

- *Question 4:* How does evapotranspiration vary in response to seasonal precipitation across these geomorphic surfaces, and how do direct measurements of actual evapotranspiration (ET_a) by eddy covariance methods compare against indirect estimates of potential evapotranspiration (ET_p) from physically-based equations, and against direct measurements of evaporation (ET_{pan}) from pan evaporimeters?

Direct measurements of actual evapotranspiration by eddy covariance methods are provided in Figures 8c and 14a-d. Based on our analyses to date, actual seasonal water vapor flux as measured by eddy covariance methods is generally highest following convective precipitation during summer months across both geomorphic surfaces, albeit fluxes above active wash surfaces are approximately double those over relict terrace surfaces in response to both summer convective and winter frontal precipitation. (Figures 8d and 14a-d). During wetter fall and winter seasons (2007-08 and 2008-09), however, evapotranspiration following storm events is substantial and in some cases greater than summer evapotranspiration (Figures 14b-d). Data analysis of the wettest winter recorded (2010) is incomplete at this time, and is therefore not reported here; however, it is suspected that winter 2010 evapotranspiration rates are among the highest recorded during the study period. Estimates of potential evapotranspiration via indirect measurements of meteorological variables and Penman-Monteith equation are provided in Figures 9-10c and Figures 15-16a-d, and via pan evaporimeters, in Figure 17a-d. Because of varying gaps in datasets for each of the different methodological approaches, annual totals of evapotranspiration are not available. Therefore only relative differences and a general range of values for each measurement type are presented and discussed here for 2008, the period of record for which data are most complete.

Annual evapotranspiration in 2008 as estimated by eddy covariance methods was roughly 40-50 mm/yr across relict pavement surfaces; over active washes, actual evapotranspiration estimates were calculated as more than double those for relict terraces, at 100-110 mm/yr. Estimates of potential evapotranspiration from Penman-Monteith are also more than double on active wash surfaces relative to relict terrace surfaces, but absolute values are still being investigated. These relative values support the notion that the vegetative contribution to evapotranspiration is substantial and plays an important eco-hydrological role in Yuma Wash, particularly in active wash surfaces. Pan evaporimeter estimates averaged 2250 mm/yr 2007-08 when pans were covered with screen mesh (versus 2625 mm/yr in 2006 when they were uncovered). Assuming a ~15% decrease in evaporative loss from pans due to mesh coverings, pan evaporation is likely closer to ~2650 mm/yr, which is comparable to published pan values for this region. And assuming an aridity index of <0.05 for this region, and PET values that are approximately 60-70% of pan evaporation, PET should approximate at least 1700 mm/yr or greater.

Results of continued analyses of the collected data will be included in an expanded report later in 2011.

Acknowledgements

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Appendix A

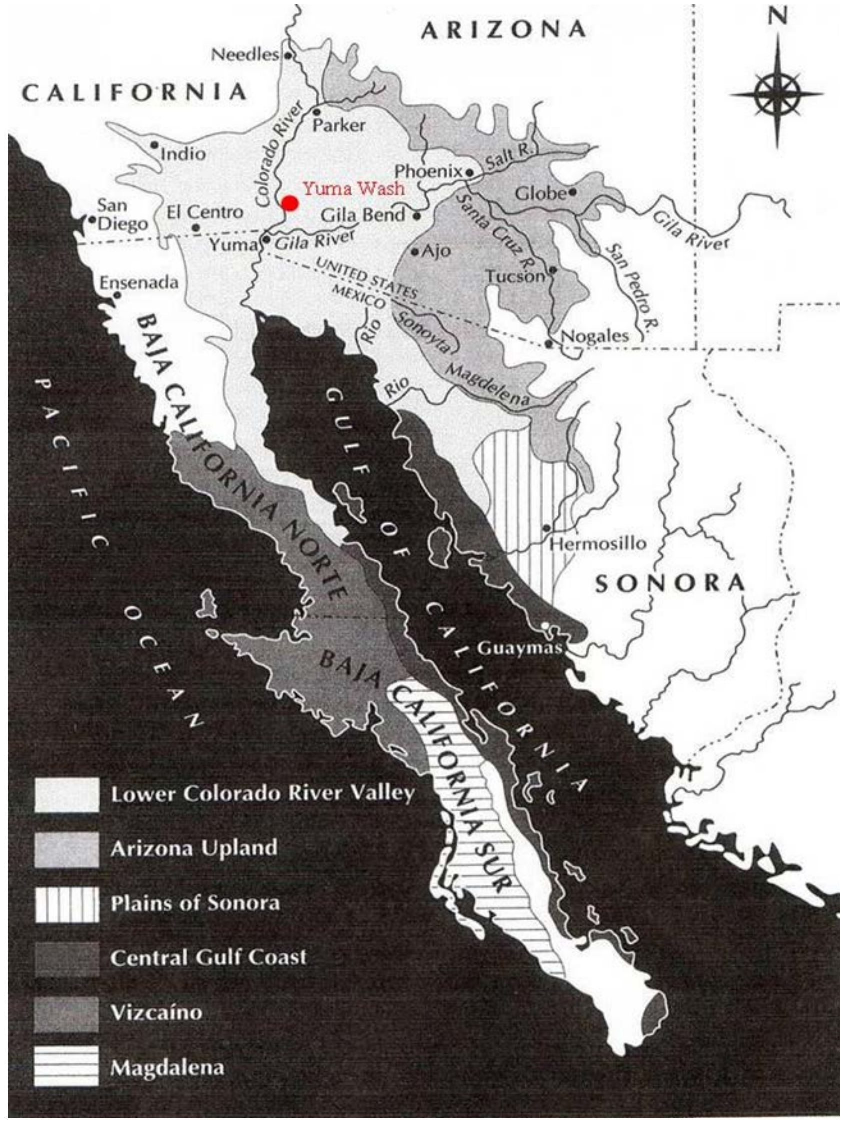


Figure 1. Physiographic location of study area Yuma Wash, Lower Colorado River Valley Subdivision, Sonoran Desert, USA.

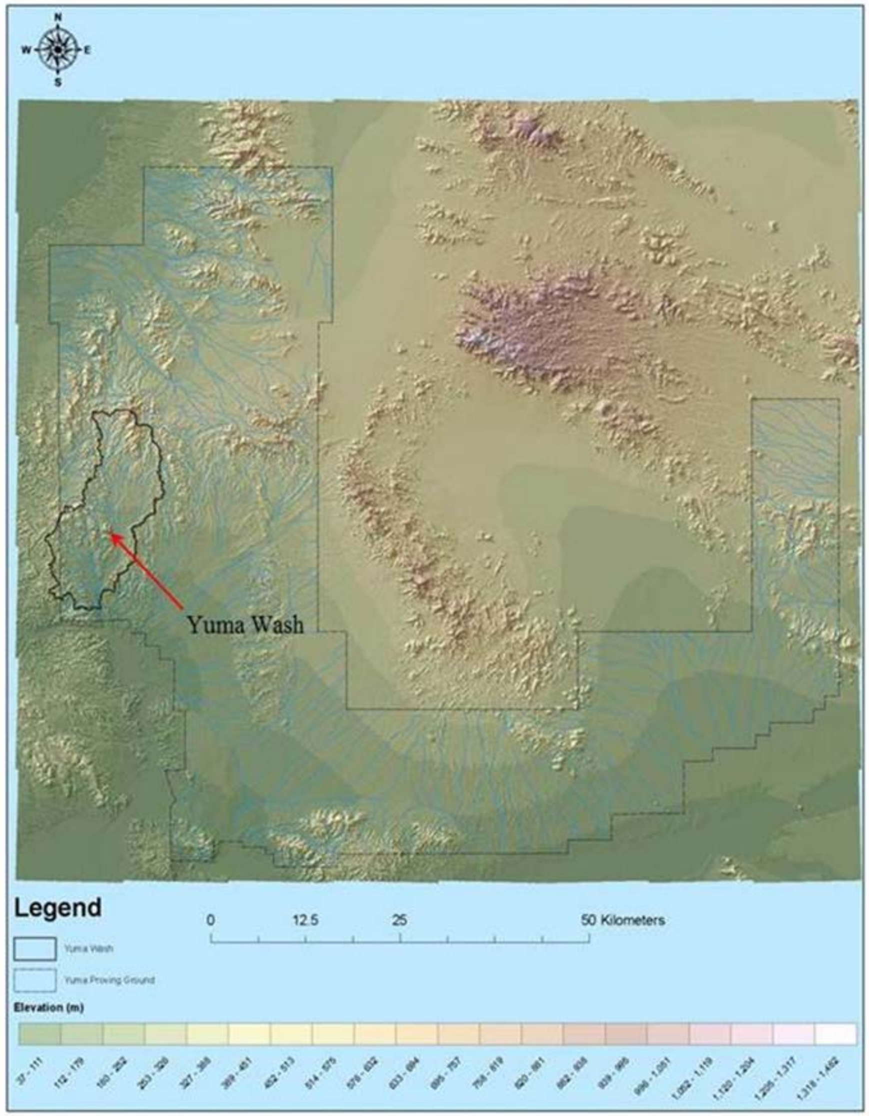


Figure 2. Political boundary of the US Army Yuma Proving Grounds and location of Yuma Wash

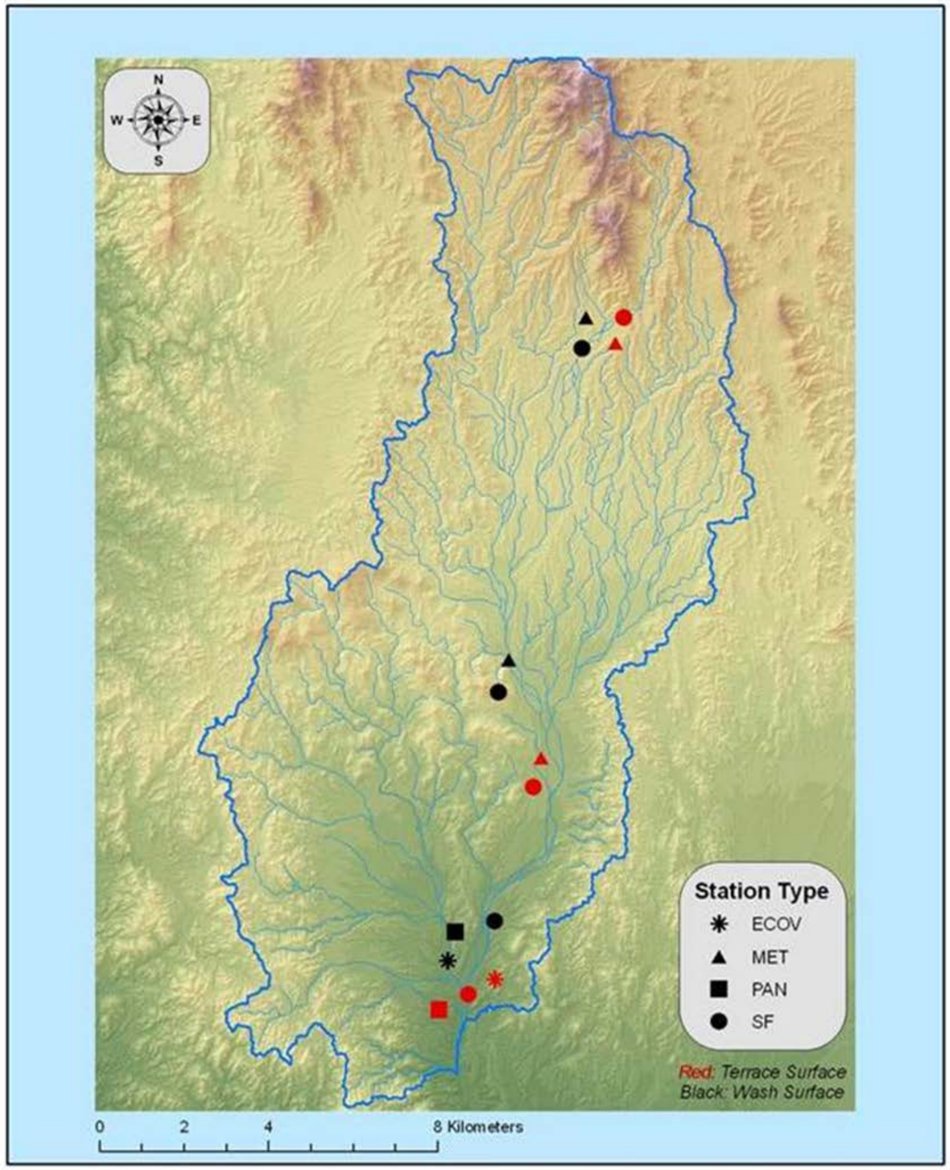


Figure 3. Hydrometeorological instrumentation deployed in Yuma Wash. ECOV are micrometeorological stations that measured actual evapotranspiration via eddy covariance techniques, MET are meteorological stations that measured variables used to estimate evapotranspiration via Penman-Monteith equation, PAN stations measured pan evaporation, and SF stations measured tree sapflux and soil moisture at 25, 50, and 100cm. Stations in red are located on relict terrace surfaces, and stations in black are located on alluvial wash surfaces.

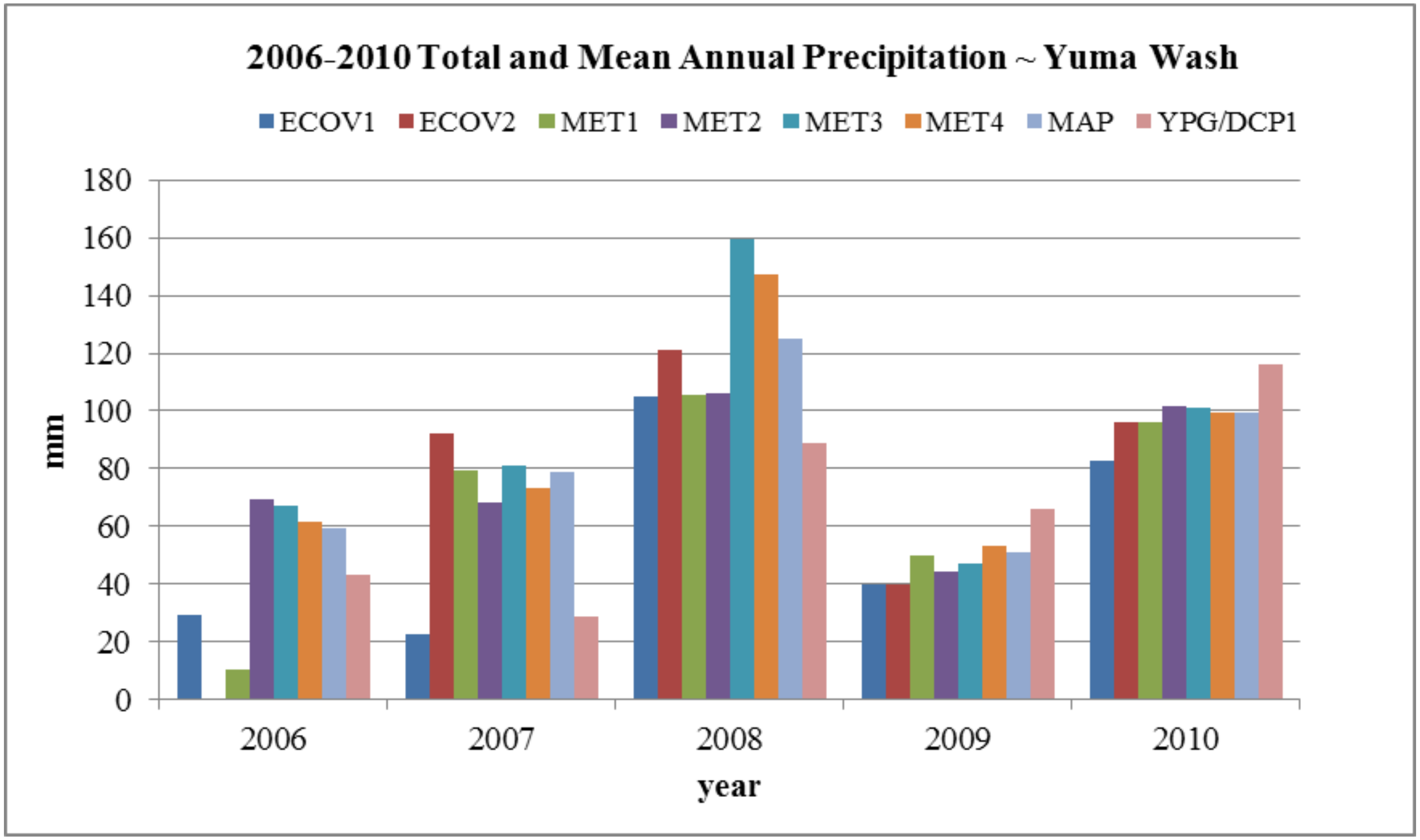


Figure 4. Total and mean annual precipitation recorded in Yuma Wash, and at the YPG/DCP1 station on the Yuma Proving Grounds from July 2006 to February 2010. Precipitation values for 2006 and 2010 are therefore partial-year totals. MET1 station also was not fully functional until October 2006, so precipitation at this station was likely higher than recorded in 2006.

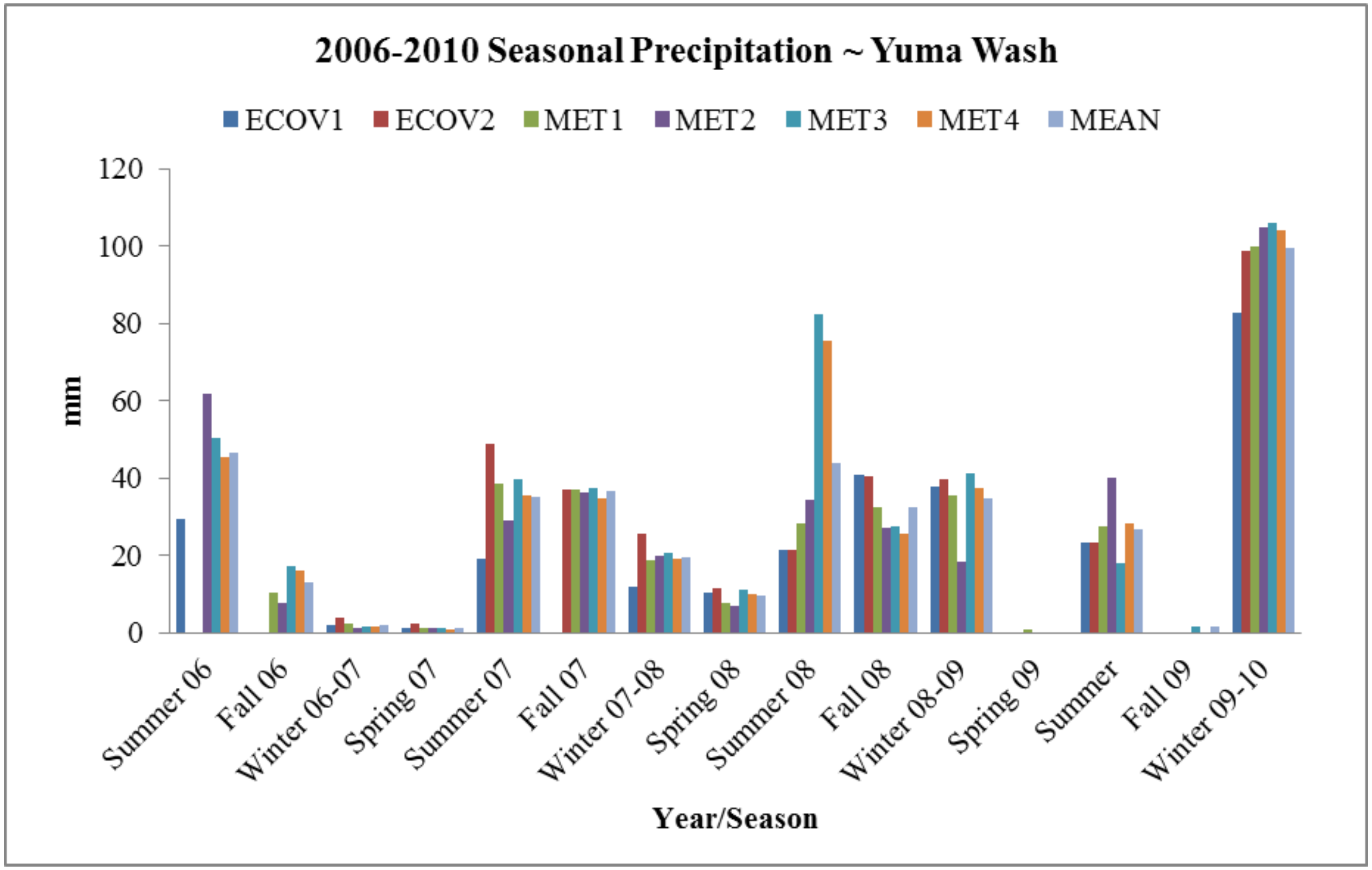


Figure 5. Seasonal precipitation recorded in Yuma Wash, from July 2006 to February 2010. MEAN refers to the six station seasonal average.

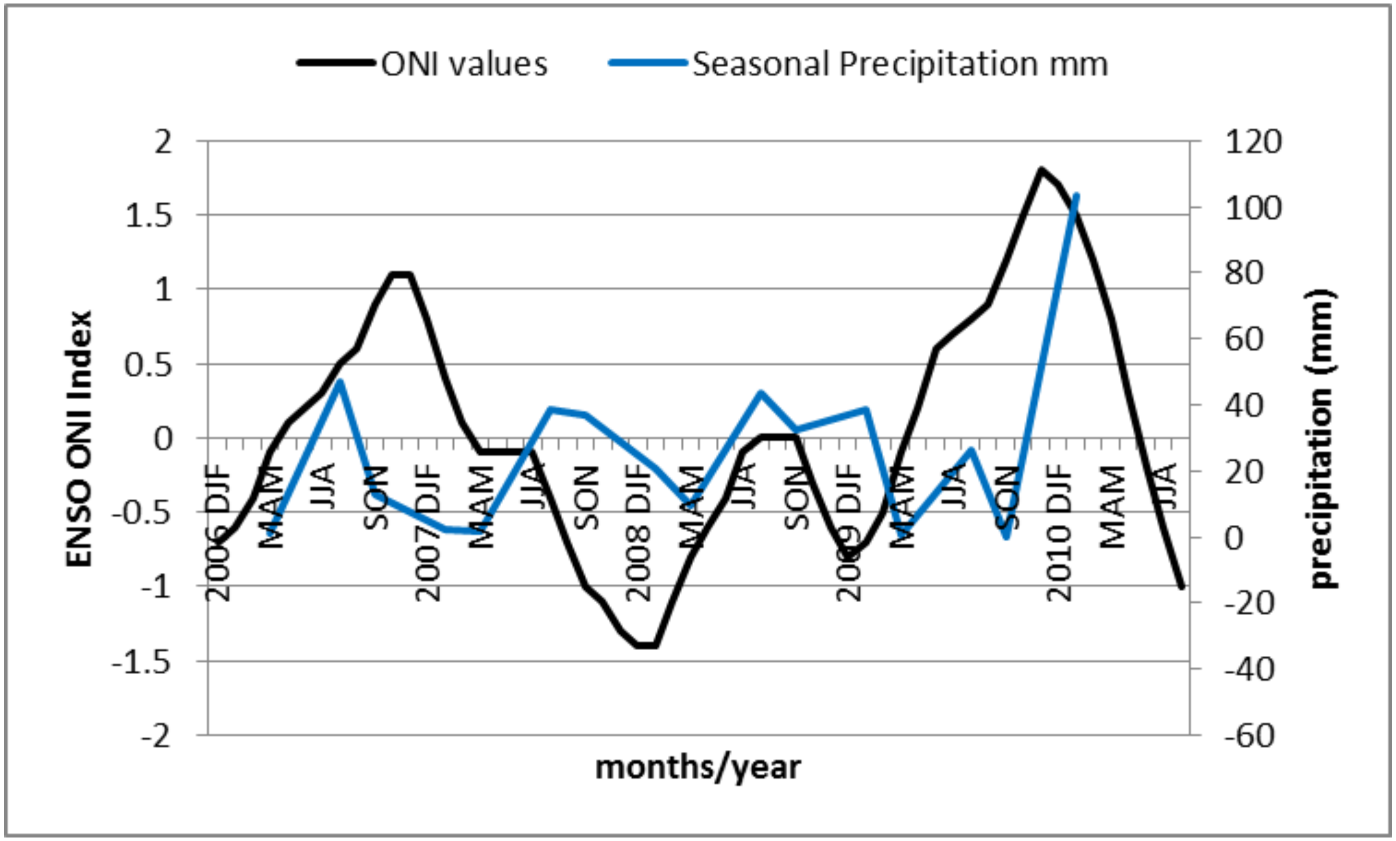


Figure 6. Comparison of ONI index values against seasonal precipitation in Yuma Wash for the period of record.

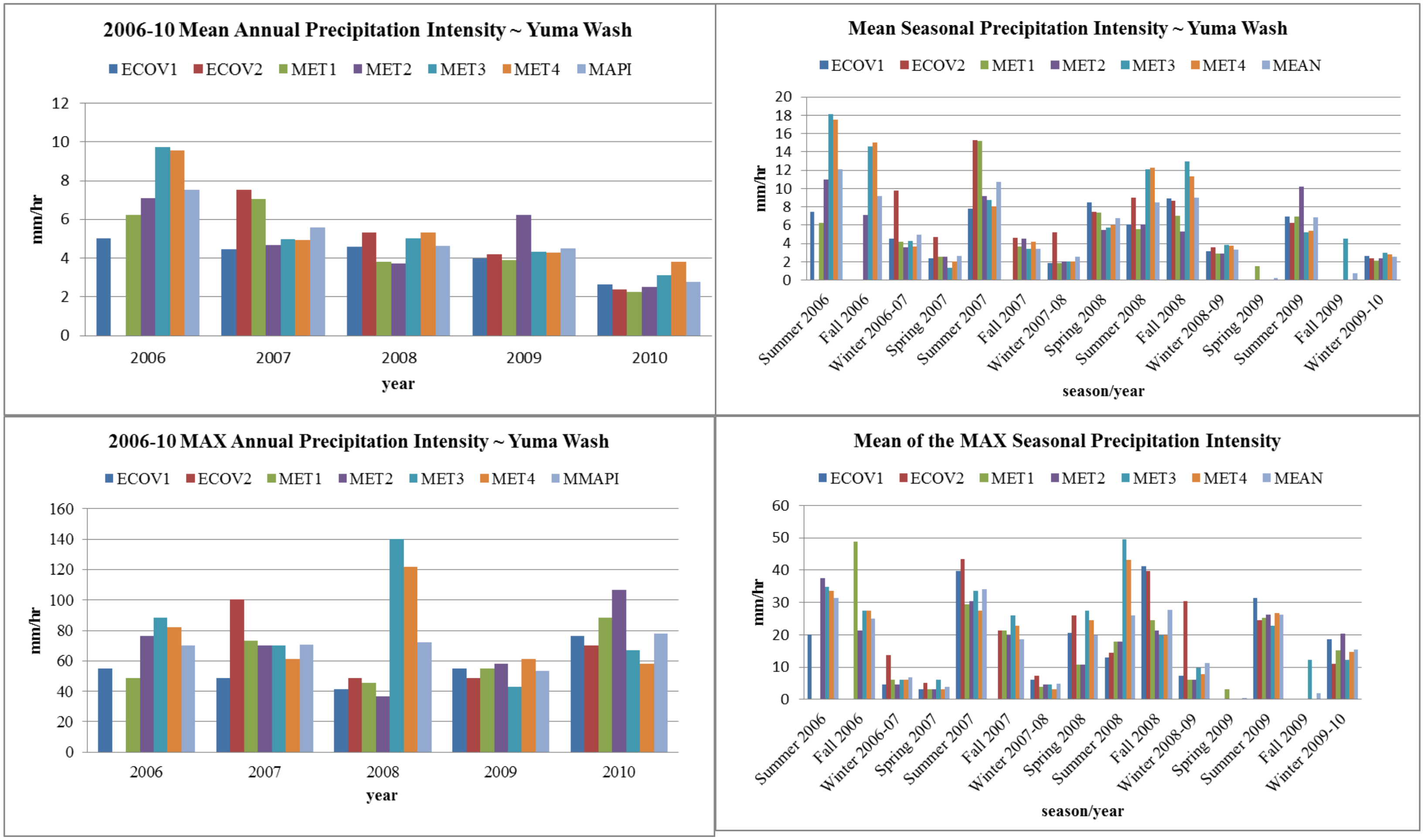
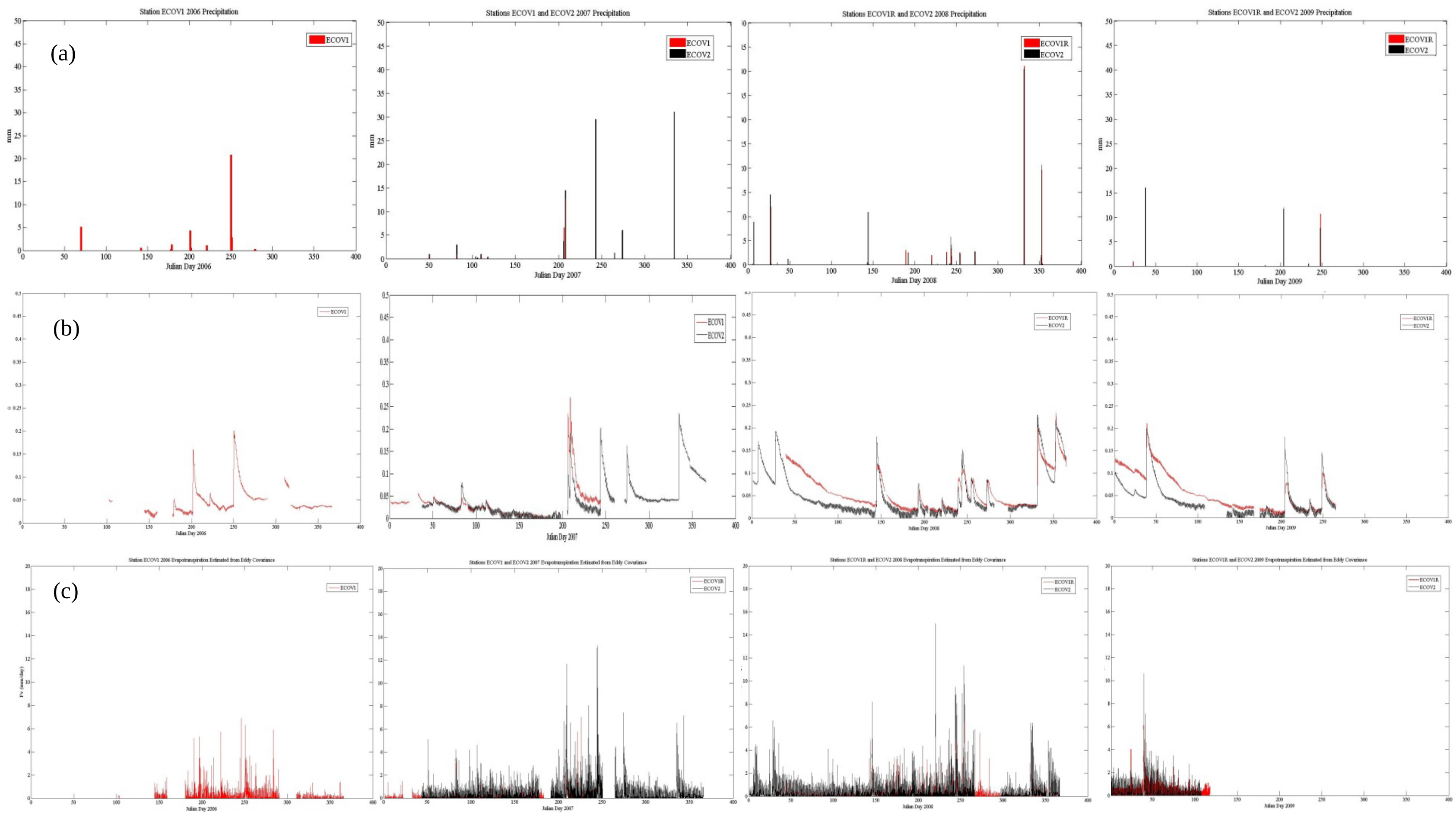
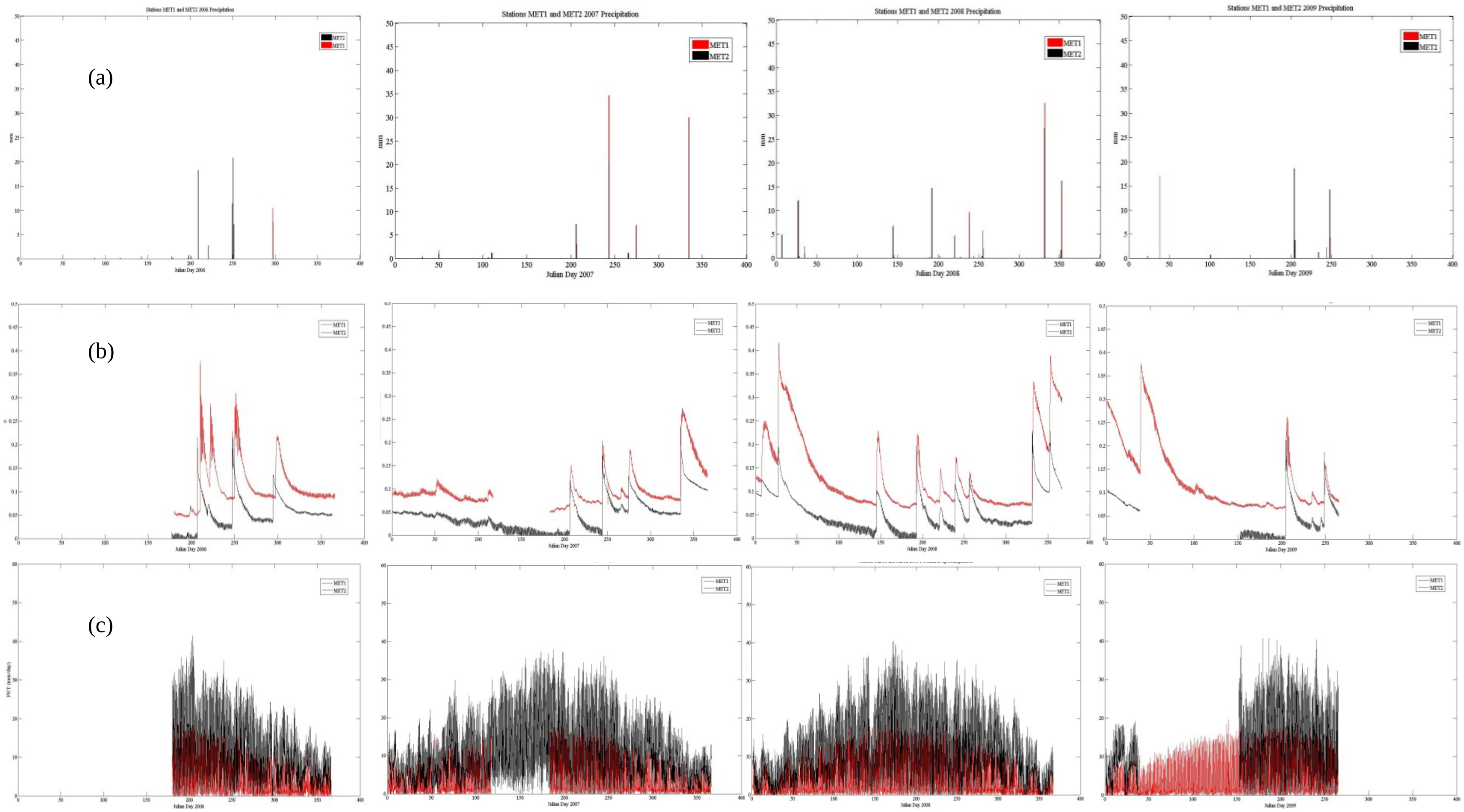


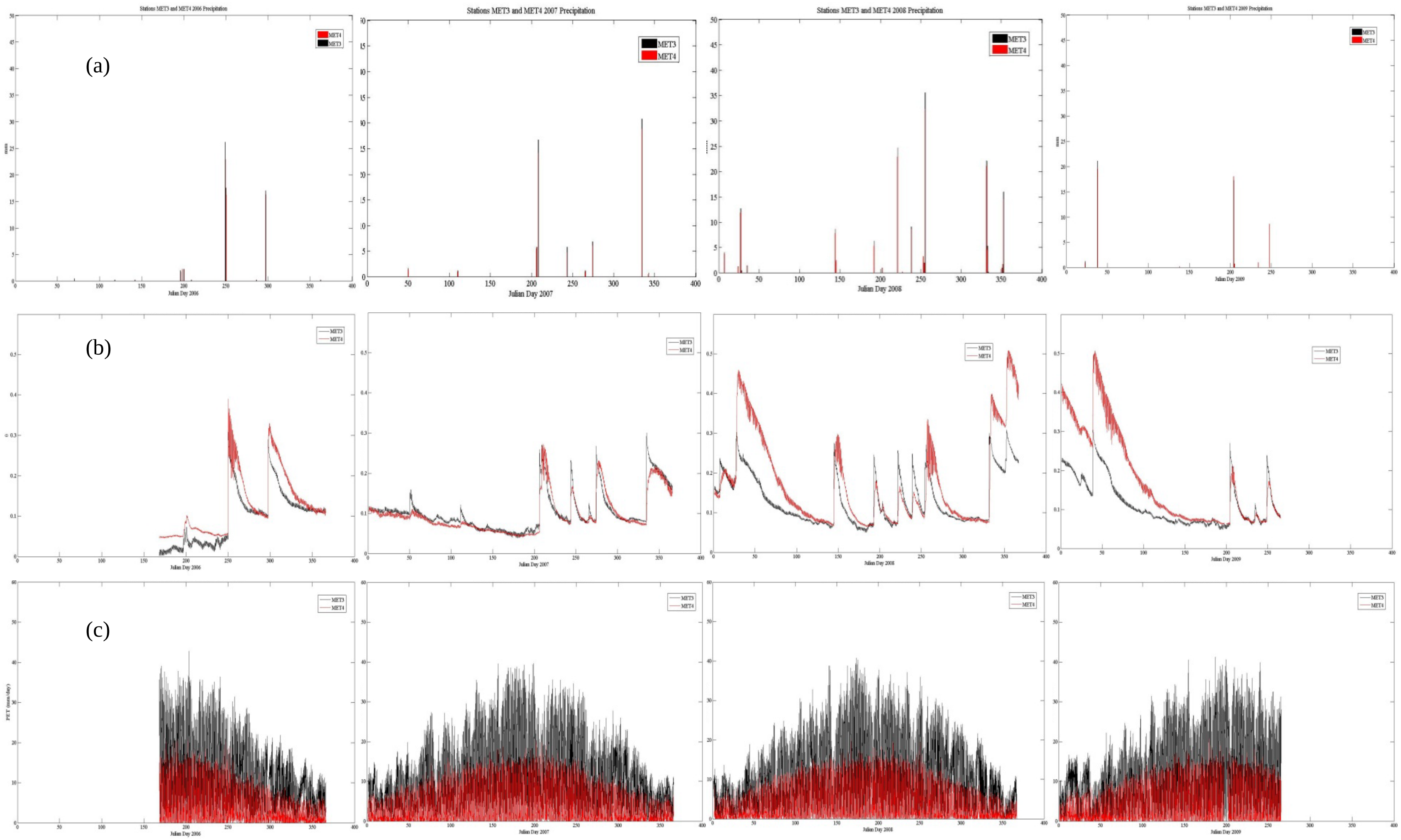
Figure 7. Mean and maximum annual and seasonal precipitation intensities (mm/yr) recorded in Yuma Wash from July 2006 to February 2010.



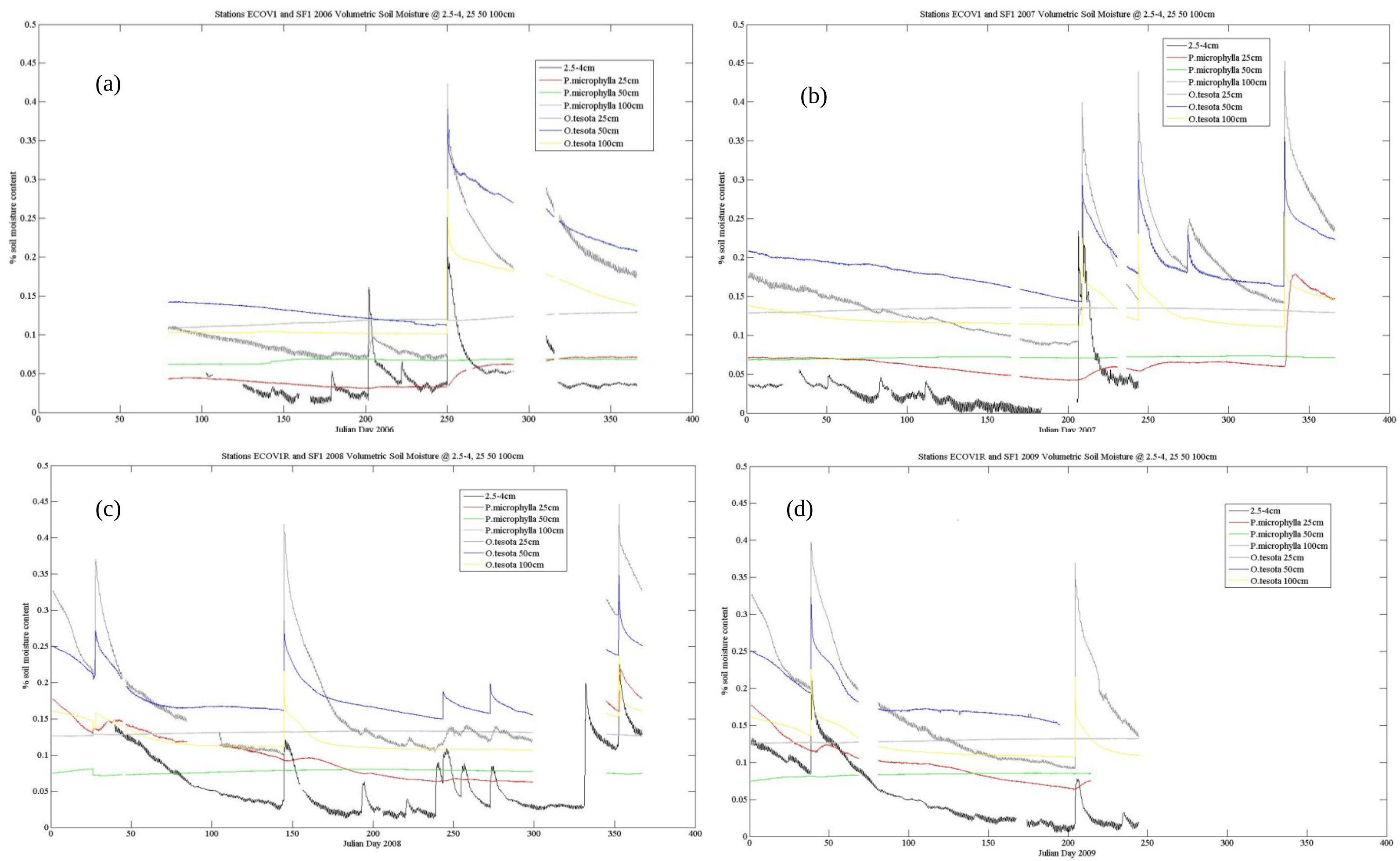
Figures 8a-c. 2006-09 (a) precipitation (mm), (b) volumetric soil moisture (θ m^3m^{-3}) @ 2.5-4cm, (c) evapotranspiration flux (mm/day) measured by eddy covariance methods. Recorded at eddy covariance micrometeorological stations ECOV1/ECOV1R (relict alluvial terrace) and ECOV2 (active alluvial wash), lower basin Yuma Wash.



Figures 9a-c. 2006-09 (a) precipitation (mm), (b) volumetric soil moisture (θ m^3m^{-3}) @ 2.5-4cm, and (c) evapotranspiration flux (mm/day) estimated from Penman-Monteith recorded at stations MET1 (relict alluvial terrace) and MET2 (active alluvial wash), mid-basin Yuma Wash.

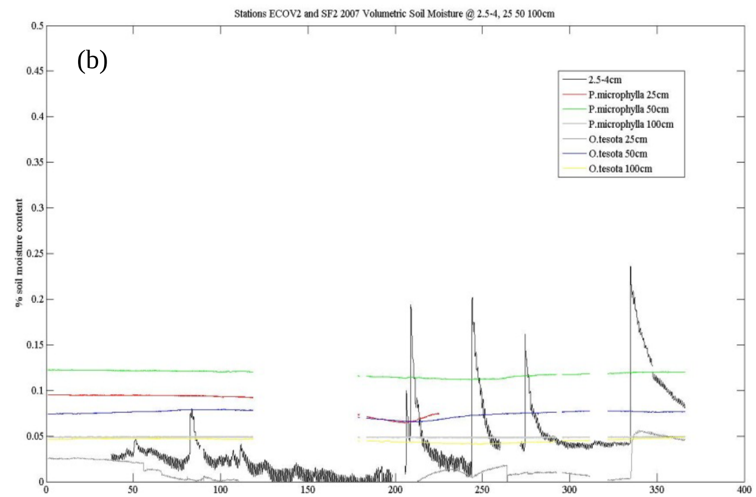


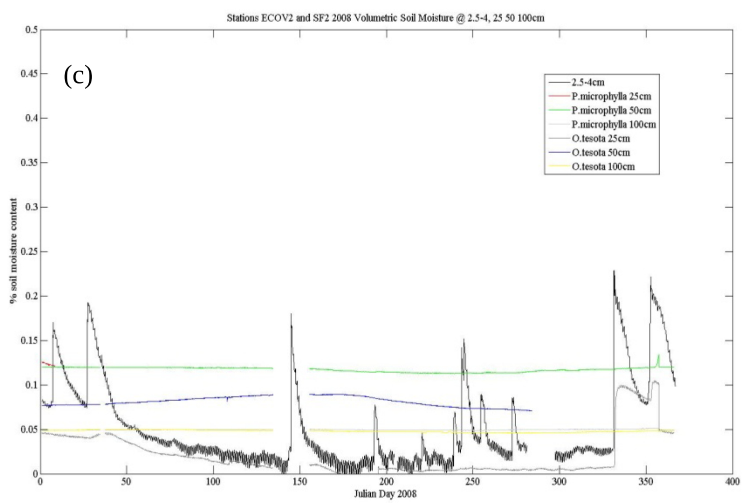
Figures 10a-c. 2006-09 (a) precipitation (mm), (b) volumetric soil moisture (θ m^3m^{-3}) @ 2.5-4cm, and (c) evapotranspiration flux (mm/day) estimated from Penman-Monteith. Recorded at stations MET3 (active alluvial wash) and MET4 (relict alluvial terrace), upper basin Yuma Wash.

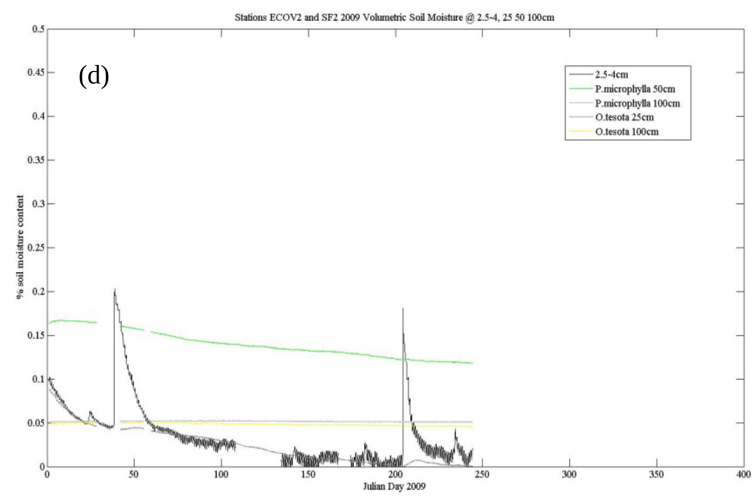


Figures 11a-d. Stations ECOV1/ECOV1R and SF1 (relict alluvial terrace). 2006-2009 volumetric soil moisture at 2.5-4cm beneath desert pavement on relict alluvial terrace, and at 25,50, and 100cm beneath *Parkinsonia microphylla* and *Olneya tesota* species in adjacent gullies on same geomorphic surface. *O.tesota* is located approximately 35m ‘upstream’ of *P.microphylla* in the same gully.

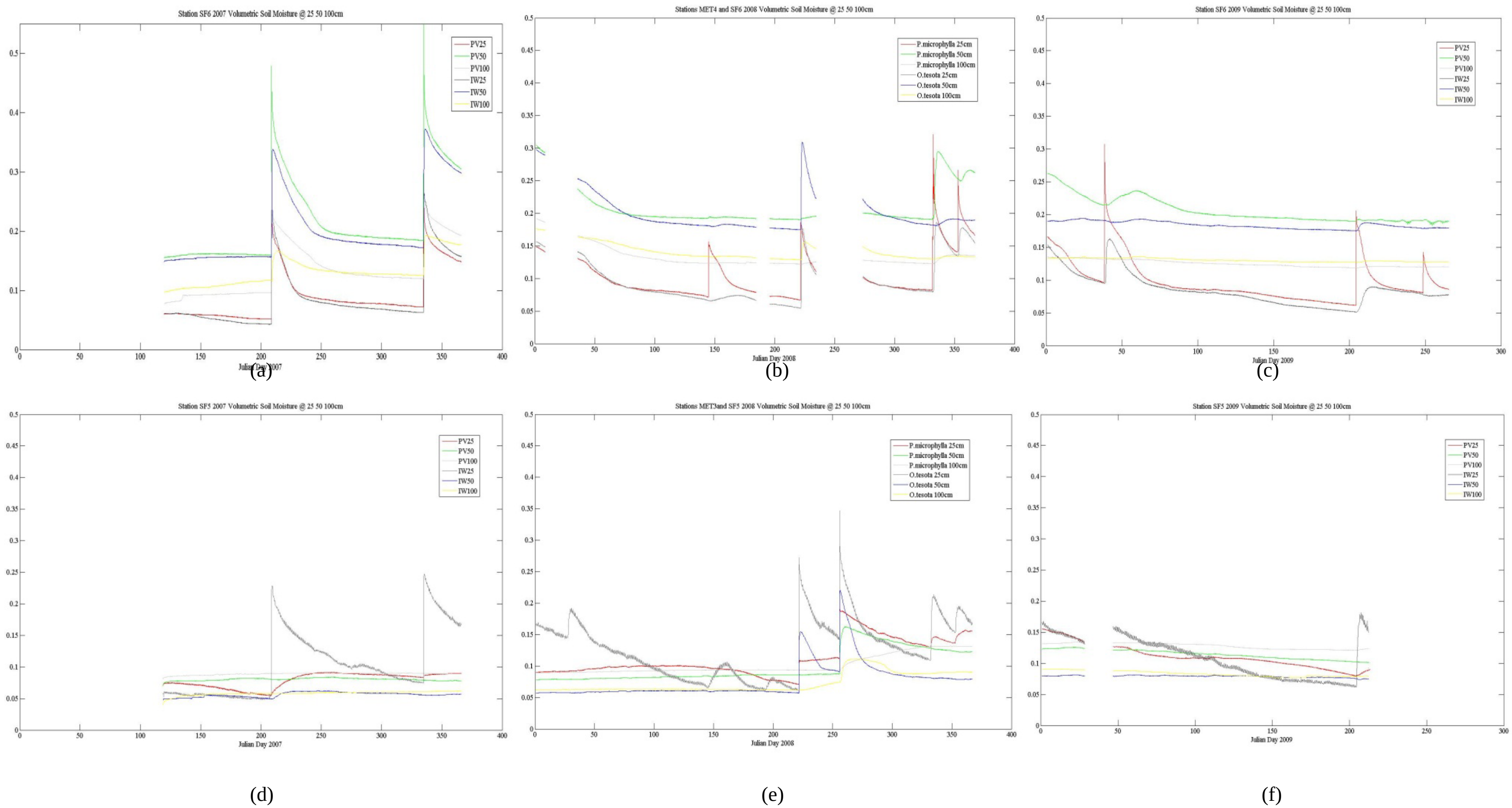
ECOV2 station not operative during 2006



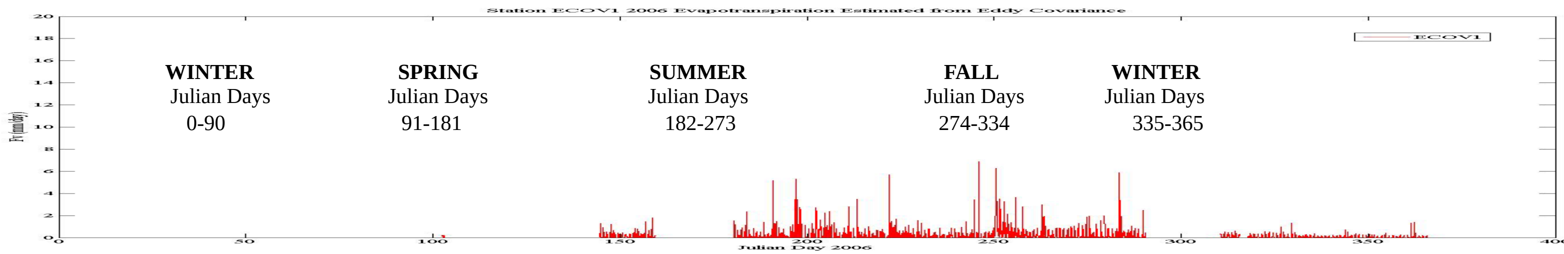




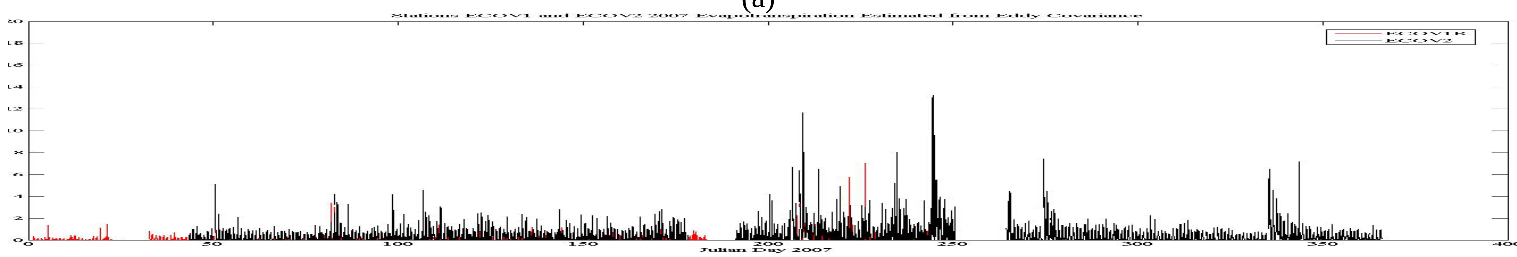
Figures 12b-d. Stations ECOV2 and SF2 (active alluvial wash). 2007-2009 volumetric soil moisture at 2.5-4cm beneath bare alluvium in active wash, and at 25,50, and 100cm beneath *Parkinsonia microphylla* and *Olneya tesota* species on adjacent interfluve on same geomorphic surface. *O.tesota* is located approximately 35m 'upstream' of P.microphylla on same interfluve.



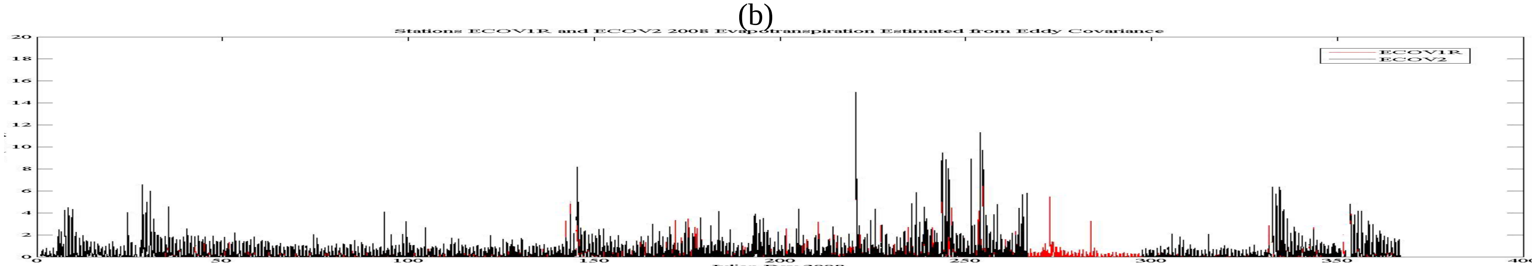
Figures 13a-f. 2007-09 volumetric soil moisture at 25,50, and 100cm beneath *Parkinsonia microphylla* and *Olneya tesota* species recorded at (a-c) station SF6 on relict terrace surface, and at (d-f) station SF5 in active alluvial wash, upper basin, Yuma Wash.



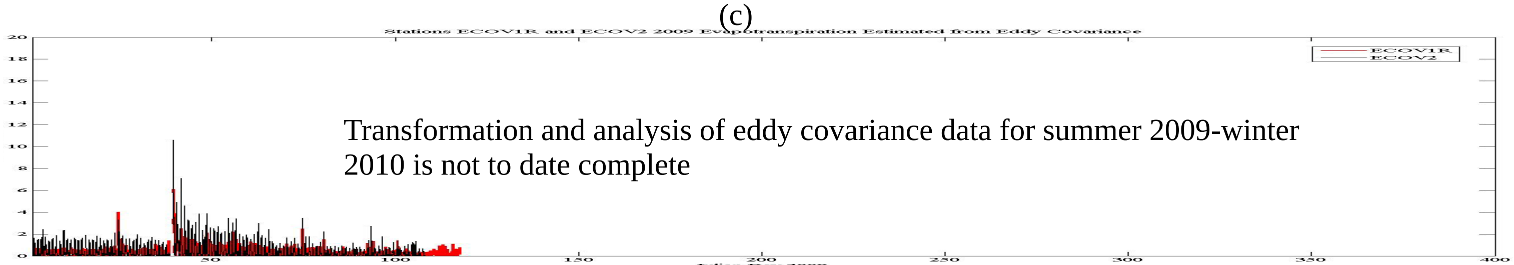
(a)



(b)

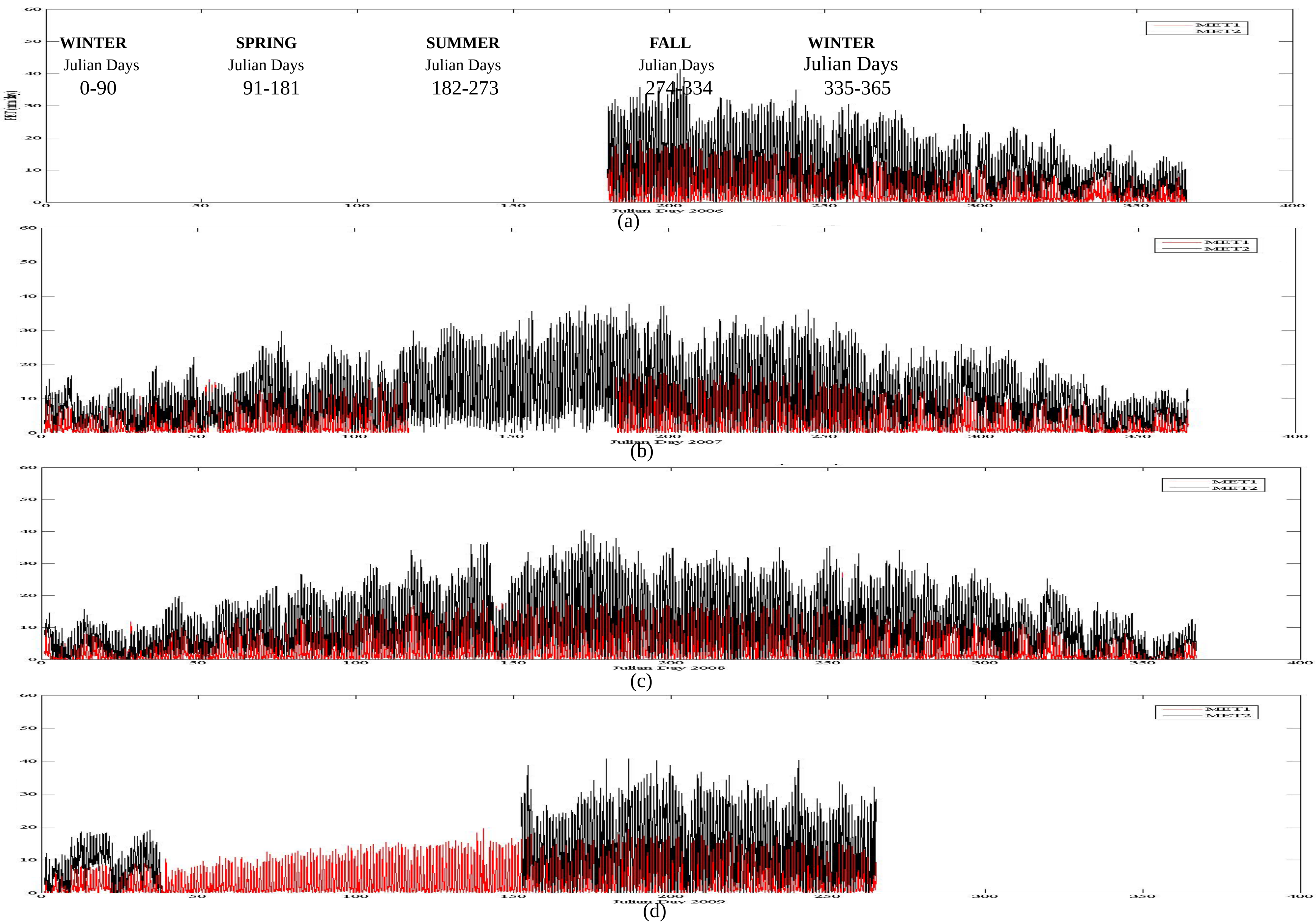


(c)

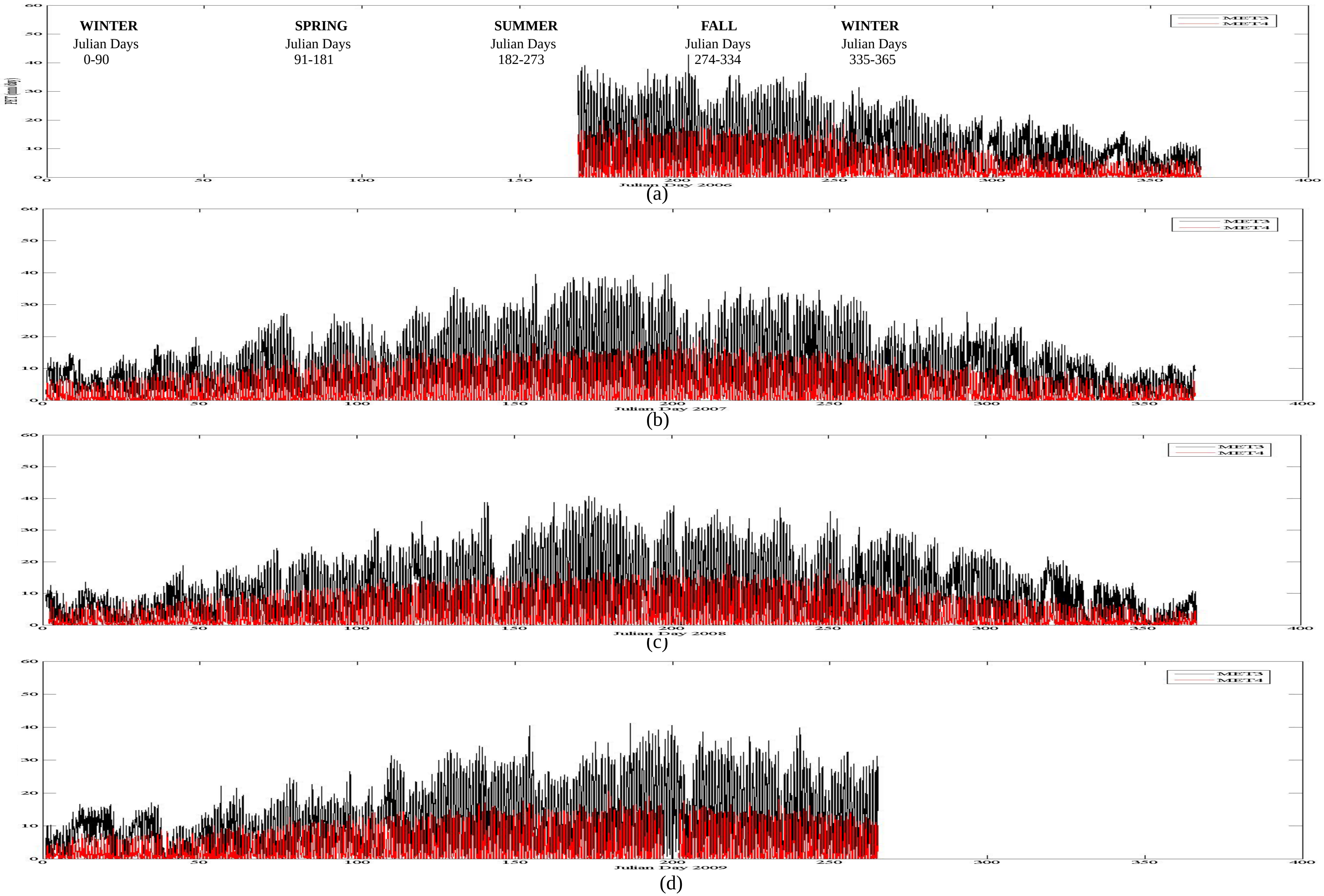


(d)

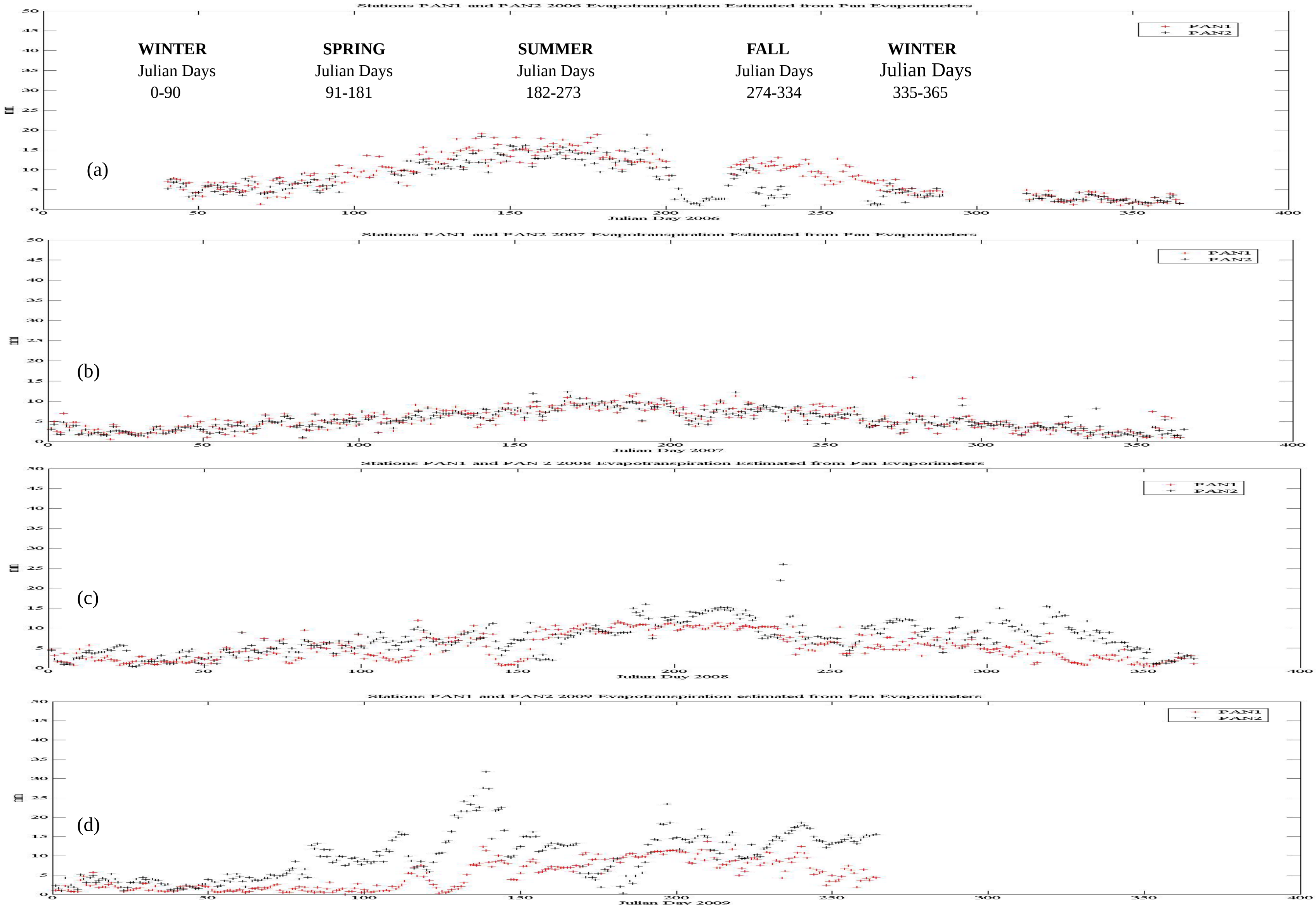
Figure 14a-d. 2006-09 evapotranspiration flux (mm/day) measured by eddy covariance methods. Recorded at eddy covariance micrometeorological stations ECOV1/ECOV1R (relict alluvial terrace in red) and ECOV2 (active alluvial wash in black), lower basin Yuma Wash.



Figures 15a-d. 2006-09 evapotranspiration flux (mm/day) estimated from Penman-Monteith. Recorded at stations MET1 (relict alluvial terrace in red) and MET2 (active alluvial wash in black), mid-basin Yuma Wash.



Figures 16a-d 2006-09 evapotranspiration flux (mm/day) estimated from Penman-Monteith recorded at stations MET3 (active alluvial wash) and MET4 (relict alluvial terrace), upper basin Yuma Wash.



Figures 17a-d. 2006-09 estimates of evapotranspiration by pan evaporimeters. Recorded at stations PAN1(relict terrace in red) and PAN2 (active alluvial wash in black).

(a) (b)

Plates 1a-b. Aerial views of geomorphic surfaces in Yuma Wash. Active (Young) alluvial wash—center in photos a and b; relict (Intermediate) alluvial terrace overlain by desert pavement and varnish—left and right in photo a, bottom and upper right in photo b); ridge and valley (Old) surfaces most visible left of center in photo b.

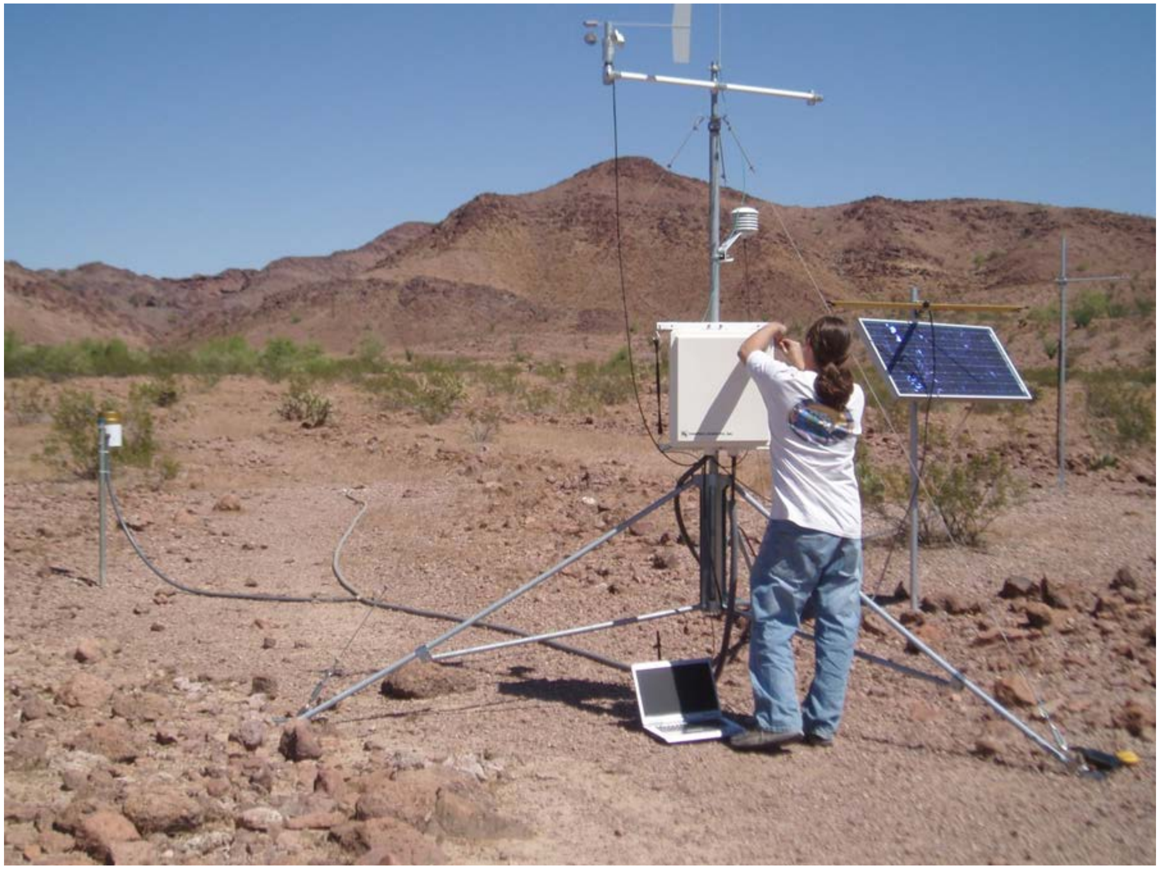


Plate 2. One of four standard meteorological stations (MET4) deployed in Yuma Wash for the duration of the study.

Plate 3. Sonic anemometers and gas analyzers on micrometeorological stations (ECOV1 and ECOV2) used to measure actual evapotranspiration in Yuma Wash via eddy covariance techniques.

Plate 4. Soil heat flux instrumentation installed at 2.5-8cm beneath the soil surface at each of six (micro) meteorological stations in Yuma Wash. Instrumentation consisted of (1) soil water content reflectometer, (4) soil temperature sensors, and (2) soil heat flux plates.

Plate 5. One of six sapflux and soil moisture stations deployed in Yuma Wash for the duration of the study.

Plate 6. Soil moisture sensors installed at 25, 50, and 100cm beneath bare ground, P.microphylla, and O.tesota at six stations in Yuma Wash.

(a) (b)

Plate 7. Sapflow sensors installed in (a) *Parkinsonia microphylla* and (b) *Olneya tesosta*. Twelve trees were instrumented (two at each of six stations) in Yuma Wash for the duration of the study.

Plate 8. One of two pan evaporimeters installed in Yuma Wash, with inset illustrating pan screen required to avoid water consumption by wildlife.

Appendix B

Statistical Analysis

STATISTICS ON SPATIAL VARIATION IN PRECIPITATION

R-square and Spearman's rank correlation (rho) of station pairs for total event precipitation (mm) recorded for period of record stations were operative.

Station	Distance (km)	Spearmans Rank Correlation			R-square
		S	p-value	Rho	
Terrace ~ Wash			(α=0.05)		
ECOV1~ECOV2	1.39	336.1913	2.202e-15	0.9383814	0.995866
MET1~MET2	1.94	1066.021	< 2.2e-16	0.9136196	0.9688537
MET4~MET3	0.1	402.7355	< 2.2e-16	0.980661	0.997186
ECOV1~MET2	7.34	7178.323	0.002013	0.4579943	0.913664
ECOV1~MET3	15.84	11969.46	0.07879	0.2618278	0.7614387
MET1~ECOV2	6.00	7251.046	4.912e-06	0.6064348	0.9563056
MET4~ECOV2	16.16	12590.22	5.557e-05	0.5200982	0.7942845
MET1~MET3	10.30	8627.173	2.885e-05	0.5598381	0.741292
MET4~MET2	8.45	15893.44	4.136e-05	0.5111065	0.7827822
Terrace ~ Terrace					
ECOV1~MET1	5.61	2638.078	0.0007181	0.5591448	0.9578862
ECOV1~MET4	15.78	11450.14	0.02015	0.3379889	0.7864093
MET1~MET4	10.24	8834.936	1.217e-05	0.5757534	0.7583926
Wash ~ Wash					
ECOV2~MET2	7.71	7359.648	6.41e-06	0.6005402	0.9373803
ECOV2~MET3	16.22	13507.57	0.0002008	0.4851317	0.7797504
MET2~MET3	8.51	16461.35	8.232e-05	0.4936373	0.7630514

Student's T and Mann-Whitney tests between station pairs for differences in event precipitation means.

Station	Mean1 (mm)	Mean2 (mm)	Students T		Mann-Whitney	
			T	**p-value** (α=0.05)	**W**	**p-value** (α=0.05)
Terrace ~ Wash						
ECOV1~ECOV2	7.84375	8.09375	-0.0691	0.9452	476.5	0.6339
MET1~MET2	7.761905	7.952381	-0.0695	0.9447	822.5	0.5933
MET4~MET3	9.16	8.60	0.2404	0.8105	1292	0.7727
ECOV1~MET2	6.232558	6.813953	-0.2167	0.8290	869.5	0.6326
ECOV1~MET3	5.608696	7.456522	-0.7088	0.4803	921	0.2766
MET1~ECOV2	7.291667	6.9375	0.1360	0.8921	1070.5	0.7597
MET4~ECOV2	6.5	7	-0.2207	0.8258	1330	0.4279
MET1~MET3	6.734694	7.979592	-0.5084	0.6124	1011.5	0.1759
MET4~MET2	6.827586	7.224138	-0.1954	0.8455	1602.5	0.6597
Terrace ~ Terrace						
ECOV1~MET1	7.666667	7.090909	0.1691	0.8663	574	0.707
ECOV1~MET4	5.978723	7.297872	-0.5279	0.5988	977.5	0.3307
MET1~MET4	6.88	7.88	-0.4246	0.6721	1076.5	0.2286
Wash ~ Wash						
ECOV2~MET2	6.979167	6.791667	0.0744	0.9409	1137.5	0.9173
ECOV2~MET3	6.351852	7.240741	-0.3844	0.7014	1297.5	0.3194
MET2~MET3	6.586207	7.534483	-0.4558	0.6494	1563	0.5087

Kolmogorov-Smirnov, F-test, and Krusal-Wallis tests between station pairs for differences in event precipitation distribution and variance (mm).

Station	Kolmogorov-Smirnov		F-test		Kruskal-Wallis	
	D	**p-value** (α=0.05)	**F**	**p-value** (α=0.05)	**chi-squared**	**p-value** (α=0.05)
Terrace ~ Wash						
ECOV1~ECOV2	0.0938	0.999	1.0132	0.971	0.2334	0.629
MET1~MET2	0.0952	0.9912	1.1482	0.6603	0.29	0.5902
MET4~MET3	0.06	1	1.0924	0.7584	0.0855	0.77
ECOV1~MET2	0.1163	0.9333	1.1892	0.577	0.2327	0.6295
ECOV1~MET3	0.1304	0.8288	1.0678	0.8267	1.1924	0.2749
MET1~ECOV2	0.0417	1	1.0917	0.7649	0.096	0.7567
MET4~ECOV2	0.1111	0.8928	1.2844	0.3651	0.6335	0.4261
MET1~MET3	0.1429	0.6994	1.1011	0.74	1.8413	0.1748
MET4~MET2	0.0862	0.9824	1.0317	0.9068	0.1964	0.6577
Terrace ~ Terrace						
ECOV1~MET1	0.0606	1	1.1603	0.6767	0.1462	0.7022
ECOV1~MET4	0.1277	0.8384	1.1766	0.5836	0.9538	0.3288
MET1~MET4	0.12	0.8643	1.182	0.5605	1.4577	0.2273
Wash ~ Wash						
ECOV2~MET2	0.1042	0.957	1.2428	0.459	0.0116	0.9143
ECOV2~MET3	0.1111	0.8928	1.1854	0.5379	0.9978	0.3179
MET2~MET3	0.1034	0.9155	0.9335	0.7958	0.4404	0.5069

Shapiro-Wilk test for normality in the distribution of total event precipitation (mm) recorded when all stations were operative.

Station	W	p-value
ECOV1	0.5574	3.015e-09
ECOV2	0.5944	1.099e-09
MET1	0.6186	4.256e-09
MET2	0.6414	1.403e-09
MET3	0.7168	2.109e-08
MET4	0.7072	1.119e-08

Spearman's rank correlation (rho) and R-square values for paired comparisons of seasonal precipitation (mm) recorded for period of record stations were operative.

Station	Distance (km)	Spearmans Rank Correlation			R-square
		S	p-value	rho	
Terrace ~ Wash					
ECOV1~ECOV2	0.40	4.0444	1.86e-10	0.9888889	0.997127
MET1~MET2	1.94	31.1369	1.278e-06	0.9315673	0.9814677
MET4~MET3	0.1	7.5134	1.286e-11	0.9865832	0.9982498
ECOV1~MET2	7.34	20.3998	8.03e-09	0.9635717	0.8859888
ECOV1~MET3	15.84	60.1482	7.611e-06	0.8925925	0.769945
MET1~ECOV2	6.00	15.5427	2.876e-07	0.9573003	0.9839217
MET4~ECOV2	16.16	54.1488	0.0002234	0.8512397	0.843327
MET1~MET3	10.30	37.1019	3.067e-05	0.8980716	0.8858563
MET4~MET2	8.45	10.5848	1.177e-10	0.9810985	0.9189888
Terrace ~ Terrace					
ECOV1~MET1	5.61	13.1067	1.141e-07	0.9639926	0.9721718
ECOV1~MET4	15.78	67.2	1.516e-05	0.88	0.7862792
MET1~MET4	10.24	31.5694	1.385e-06	0.9306167	0.9035171
Wash ~ Wash					
ECOV2~MET2	7.71	72.7997	0.001025	0.8000008	0.9340909
ECOV2~MET3	16.22	45.6253	9.129e-05	0.8746556	0.8324964
MET2~MET3	8.51	30.6366	1.08e-07	0.9452919	0.9068543

Student's T and Mann-Whitney tests between station pairs for differences in seasonal precipitation means (mm).

Station	Students T				Mann-Whitney	
	Mean1	**Mean2**	**t**	**p-value**	**W**	**p-value**
Terrace ~ Wash						
ECOV1~ECOV2	18.07692	18.61538	-0.0578	0.9544	82.5	0.9383
MET1~MET2	23.07143	23.35714	-0.028	0.9779	99	0.9816
MET4~MET3	30.4	28.46667	0.1761	0.8615	122	0.7086
ECOV1~MET2	17.53333	19.26667	-0.2012	0.842	114.5	0.9499
ECOV1~MET3	16.93333	22.8	-0.6248	0.5374	100.5	0.6285
MET1~ECOV2	26.69231	25.46154	0.1151	0.9093	118.5	0.3425
MET4~ECOV2	26.69231	28.76923	-0.1807	0.8581	87.5	0.8978
MET1~MET3	25.15385	29.92308	-0.4066	0.688	76.5	0.7001
MET4~MET2	23.26667	25.8	-0.2343	0.8164	107.5	0.8513
Terrace ~ Terrace						
ECOV1~MET1	19.23077	17.84615	0.1498	0.8822	86	0.959
ECOV1~MET4	18.4	22.73333	-0.4864	0.6305	104.5	0.7534
MET1~MET4	24.35714	27.85714	-0.3279	0.7457	96.5	0.9633
Wash ~ Wash						
ECOV2~MET2	25.46154	24.53846	0.0843	0.9335	89	0.8371
ECOV2~MET3	26.07692	29.92308	-0.3248	0.7482	80.5	0.8573
MET2~MET3	23.73333	27.86667	-0.3759	0.7098	101.5	0.6625

Kolmogorov-Smirnov, F-test, and Kruskal-Wallis tests between station pairs for differences in seasonal precipitation distribution and/or variance (mm).

Station	Kolmogorov-Smirnov		F-test		Kruskal-Wallis	
	D	**p-value**	**F**	**p-value**	**chi-squared**	**p-value**
Terrace ~ Wash						
ECOV1~ECOV2	0.0769	1	1.0133	0.982	0.0107	0.9178
MET1~MET2	0.0714	1	0.8878	0.8334	0.0021	0.9633
MET4~MET3	0.1333	0.9993	1.0962	0.866	0.1556	0.6932
ECOV1~MET2	0.1333	0.9993	0.7863	0.659	0.007	0.9332
ECOV1~MET3	0.1333	0.9993	0.6827	0.4843	0.2549	0.6136
MET1~ECOV2	0.1538	0.9979	1.0279	0.9627	0.9456	0.3308
MET4~ECOV2	0.1538	0.9979	0.7809	0.6752	0.0238	0.8775
MET1~MET3	0.2308	0.8793	0.6941	0.5368	0.1688	0.6812
MET4~MET2	0.1333	0.9993	0.929	0.8923	0.0434	0.835
Terrace ~ Terrace						
ECOV1~MET1	0.1538	0.9979	1.0374	0.9503	0.006	0.9384
ECOV1~MET4	0.2	0.925	0.768	0.628	0.1123	0.7375
MET1~MET4	0.0714	1	0.7688	0.6424	0.0048	0.945
Wash ~ Wash						
ECOV2~MET2	0.1538	0.9979	0.9056	0.8664	0.0535	0.8171
ECOV2~MET3	0.0769	1	0.7264	0.5884	0.0422	0.8372
MET2~MET3	0.2	0.925	0.8335	0.7381	0.2091	0.6475

Shapiro-Wilks tests for normality in the distribution of seasonal precipitation (mm) recorded when all stations were operative.

Station	W	p-value
ECOV1	0.8028	0.00399
ECOV2	0.8494	0.02799
MET1	0.7959	0.004444
MET2	0.8265	0.008201
MET3	0.8624	0.02617
MET4	0.8618	0.02559

R-square and Spearman's rank correlation (rho) of station pairs for mean precipitation intensity (mm/hr) recorded for period of record station pairs were operative.

Station	Distance (km)	Spearmans Rank Correlation			R-square
		S	p-value	Rho	
Terrace ~ Wash			(α=0.05)		
ECOV1~ECOV2	1.39	2087.288	0.0001668	0.6174325	0.5988663
MET1~MET2	1.94	4479.299	5.733e-06	0.6370392	0.7942747
MET4~MET3	0.1	3237.183	1.283e-14	0.844553	0.982807
ECOV1~MET2	7.34	13626.73	0.854	-0.02889837	0.1000342
ECOV1~MET3	15.84	20750.87	0.05973	-0.2797329	-0.1577079
MET1~ECOV2	6.00	16855.17	0.565	0.08515128	0.7313916
MET4~ECOV2	16.16	27907.35	0.647	-0.06374499	0.01945886
MET1~MET3	10.30	19655.04	0.9847	-0.002807919	0.1107593
MET4~MET2	8.45	32374.29	0.9754	0.004143747	0.1343805
Terrace ~ Terrace					
ECOV1~MET1	5.61	4790.285	0.2657	0.1994844	0.3479342
ECOV1~MET4	15.78	21059.71	0.1417	-0.2176057	-0.1433497
MET1~MET4	10.24	18039.01	0.3543	0.1337813	0.1000337
Wash ~ Wash					
ECOV2~MET2	7.71	18671.48	0.9278	-0.01343235	0.4624106
ECOV2~MET3	16.22	30229.74	0.2717	-0.1522677	0.03502634
MET2~MET3	8.51	33990	0.7342	-0.04555654	0.1304941

R-square and Spearman's rank correlation (rho) of station pairs for maximum precipitation intensity (mm/hr) recorded for period of record station pairs were operative.

Station	Distance (km)	Spearmans Rank Correlation			R-square
		S	p-value	Rho	
Terrace ~ Wash			(α=0.05)		
ECOV1~ECOV2	1.39	1317.631	4.911e-07	0.7584986	0.9286423
MET1~MET2	1.94	2300.938	5.813e-11	0.8135534	0.8696386
MET4~MET3	0.1	2857.224	7.958e-16	0.8627984	0.9300706
ECOV1~MET2	7.34	11341.25	0.358	0.1436688	0.519203
ECOV1~MET3	15.84	15097.62	0.6491	0.06891023	0.8671074
MET1~ECOV2	6.00	13353.92	0.05835	0.275189	0.8066594
MET4~ECOV2	16.16	21754.20	0.2169	0.1707949	0.7317522
MET1~MET3	10.30	13765.21	0.0377	0.2976934	0.69481
MET4~MET2	8.45	23426.81	0.03368	0.2793748	0.7592032
Terrace ~ Terrace					
ECOV1~MET1	5.61	4044.408	0.06574	0.3241297	0.6853189
ECOV1~MET4	15.78	15601.17	0.5123	0.09798944	0.3227507
MET1~MET4	10.24	12040.32	0.00228	0.4218332	0.3534753
Wash ~ Wash					
ECOV2~MET2	7.71	14310.65	0.1272	0.2232604	0.6357682
ECOV2~MET3	16.22	21930.87	0.2358	0.1640607	0.3131180
MET2~MET3	8.51	26668.29	0.1772	0.1796645	0.4154594

Student's T and Mann-Whitney tests between station pairs for differences in mean precipitation intensities.

Station	Mean1	Mean2	Students T		Mann-Whitney	
	(mm)	(mm)	*T*	p-value (α=0.05)	W	p-value (α=0.05)
Terrace ~ Wash						
ECOV1~ECOV2	4.84375	6.15625	-1.2941	0.2007	437	0.3123
MET1~MET2	4.547619	4.809524	-0.2156	0.8299	744.5	0.2124
MET4~MET3	7.10	6.74	0.2213	0.8254	1335	0.5568
ECOV1~MET2	4.465116	5	-0.5256	0.6007	927.5	0.9826
ECOV1~MET3	3.869565	6.347826	-1.7533	0.08451	944	0.3675
MET1~ECOV2	5.583333	3.916667	1.221	0.2252	1076.5	0.724
MET4~ECOV2	5.074074	4.518519	0.4594	0.6469	1531	0.6526
MET1~MET3	3.714286	5.081633	-1.1222	0.2646	914	**0.03944**
MET4~MET2	4.793103	5.913793	-0.8956	0.3726	1626.5	0.7595
Terrace ~ Terrace						
ECOV1~MET1	4.424242	3.727273	0.7945	0.4299	611	0.3910
ECOV1~MET4	4.085106	6.085106	-1.443	0.1539	1043.5	0.6432
MET1~MET4	3.94	5.18	-1.0354	0.3031	1035	0.1349
Wash ~ Wash						
ECOV2~MET2	5.625	4.000	1.3413	0.1836	1316.5	0.224
ECOV2~MET3	4.870370	4.611111	0.2113	0.833	1451.5	0.9702
MET2~MET3	4.465517	6.051724	-1.2832	0.2025	1537	0.4205

Kolmogorov-Smirnov, F-test, and Krusal-Wallis tests between station pairs for differences in distribution and variance of mean precipitation intensities (mm/hr).

Station	Kolmogorov-Smirnov		F-test		Kruskal-Wallis	
	D	**p-value**	**F**	**p-value**	**chi-squared**	**p-value**
Terrace ~ Wash		(α=0.05)		(α=0.05)		(α=0.05)
ECOV1~ECOV2	0.1562	0.8296	0.5989	0.1591	1.0346	0.3091
MET1~MET2	0.1429	0.7848	2.1506	0.01604	1.5665	0.2107
MET4~MET3	0.08	0.9972	1.0021	0.9941	0.3494	0.5544
ECOV1~MET2	0.1333	0.9993	0.5283	0.04153	7e-04	0.979
ECOV1~MET3	0.1522	0.6612	0.1924	1.709e-07	0.8192	0.3654
MET1~ECOV2	0.1875	0.3676	1.2824	0.3971	0.1276	0.721
MET4~ECOV2	0.0741	0.9984	1.489	0.1506	0.2054	0.6504
MET1~MET3	0.1837	0.3802	1.1013	0.7395	4.2567	**0.0391**
MET4~MET2	0.069	0.9991	0.4513	0.003152	0.0954	0.7574
Terrace ~ Terrace						
ECOV1~MET1	0.1212	0.9686	1.193	0.6206	0.7469	0.3875
ECOV1~MET4	0.1277	0.8384	0.2096	4.776e-07	0.2182	0.6404
MET1~MET4	0.14	0.7112	1.1076	0.722	2.2457	0.1340
Wash ~ Wash						
ECOV2~MET2	0.1667	0.5176	2.4782	0.002336	1.4877	0.2226
ECOV2~MET3	0.0926	0.9748	1.4212	0.204	0.0016	0.9677
MET2~MET3	0.1034	0.9155	0.3927	0.0005567	0.6534	0.4189

Student's T and Mann-Whitney tests between station pairs for differences in maximum precipitation intensities.

Station	Mean1 (mm)	Mean2 (mm)	Students T		Mann-Whitney	
			T	p-value (α=0.05)	W	p-value (α=0.05)
Terrace ~ Wash						
ECOV1~ECOV2	15.9375	16.0000	-0.0139	0.989	467.5	0.5517
MET1~MET2	14.90476	16.30952	-0.3148	0.7537	837.5	0.6875
MET4~MET3	20.98	20.34	0.1224	0.9029	1335.5	0.5534
ECOV1~MET2	14.09302	16.93023	-0.6126	0.5419	916	0.9441
ECOV1~MET3	12.34783	20.13043	-1.5114	0.1350	911.5	0.2477
MET1~ECOV2	14.39583	12.20833	0.5563	0.5793	1078.5	0.7115
MET4~ECOV2	12.90741	15.98148	-0.7276	0.4686	1449	0.9578
MET1~MET3	11.59184	18.20408	-1.4109	0.1620	971	0.09935
MET4~MET2	16.31034	17.91379	-0.3618	0.7182	1619.5	0.7286
Terrace ~ Terrace						
ECOV1~MET1	15.18182	12.63636	0.5561	0.5801	597	0.5
ECOV1~MET4	13.00000	18.61702	-1.1876	0.2385	1007.5	0.4599
MET1~MET4	12.76	17.80	-1.1496	0.2533	1097	0.2855
Wash ~ Wash						
ECOV2~MET2	14.33333	13.77083	0.1354	0.8926	1253.5	0.4534
ECOV2~MET3	12.51852	16.51852	-0.8946	0.3732	1369.5	0.5841
MET2~MET3	15.31034	18.46552	-0.6852	0.4947	1535.5	0.4151

Kolmogorov-Smirnov, F-test, and Krusal-Wallis tests between station pairs for differences in distribution and variance of maximum precipitation intensities (mm/hr).

Station	Kolmogorov-Smirnov		F-test		Kruskal-Wallis	
	D	p-value	F	p-value	chi-squared	p-value
Terrace ~ Wash		(α=0.05)		(α=0.05)		(α=0.05)
ECOV1~ECOV2	0.1562	0.8296	1.1268	0.7418	0.3624	0.5472
MET1~MET2	0.0952	0.9912	0.878	0.6789	0.1655	0.6841
MET4~MET3	0.12	0.8643	1.0786	0.7923	0.3555	0.551
ECOV1~MET2	0.1163	0.9333	0.5892	0.09022	0.0055	0.9406
ECOV1~MET3	0.1957	0.3421	0.3604	0.00085	1.3454	0.2461
MET1~ECOV2	0.125	0.8475	1.1961	0.5417	0.1398	0.7085
MET4~ECOV2	0.1296	0.7547	0.6425	0.1104	0.0031	0.9553
MET1~MET3	0.1837	0.3802	0.4496	0.00654	2.7279	0.09861
MET4~MET2	0.0517	1	0.8242	0.4677	0.1223	0.7265
Terrace ~ Terrace						
ECOV1~MET1	0.1212	0.9686	1.0016	0.9965	0.4638	0.4958
ECOV1~MET4	0.1277	0.8384	0.4502	0.00787	0.5518	0.4576
MET1~MET4	0.12	0.8643	0.581	0.06022	1.1481	0.2840
Wash ~ Wash						
ECOV2~MET2	0.1458	0.6871	0.958	0.8838	0.5678	0.4511
ECOV2~MET3	0.1111	0.8928	0.5407	0.02705	0.3031	0.5819
MET2~MET3	0.1379	0.6393	0.6575	0.1164	0.6687	0.4135

Shapiro-Wilks test for normality of mean and maximum precipitation intensity for the period of record stations were operative.

Station	$W_{mean\ int}$	p-value$_{mean\ int}$	$W_{max\ int}$	p-value$_{max\ int}$
ECOV1	0.88	0.001013	0.7749	5.366e-06
ECOV2	0.611	1.884e-09	0.6531	7.918e-09
MET1	0.4892	9.215e-11	0.673	2.760e-08
MET2	0.7658	2.381e-07	0.7335	5.451e-08
MET3	0.6677	2.911e-09	0.6884	6.555e-09
MET4	0.6699	2.477e-09	0.7343	3.600e-08

STATISTICS ON TEMPORAL VARIATION IN PRECIPITATION

Student's t and Mann-Whitney tests for differences in means of interannual precipitation.

Season			**Student's t**		**Mann-Whitney**	
	Mean1	**Mean2**	***t***	**p-value**	**W**	**p-value**
Winter06_07 ~ Winter07_08	2.17	19.33	-9.6894	**0.0001113**	0	**0.004267**
Winter06_07 ~ Winter08_09	2.17	35	-9.4152	**0.0001975**	0	**0.004267**
Winter06_07 ~ Winter09_10	2.17	99.67	-27.3174	**9.41e-07**	0	**0.004267**
Winter07_08 ~ Winter08_09	19.33	35	-4.0481	**0.004424**	5	**0.04458**
Winter07_08 ~ Winter09_10	19.33	99.67	-20.3682	**1.167e-07**	0	**0.004922**
Winter08_09 ~ Winter09_10	35	99.67	-13.044	**1.336e-07**	0	**0.004922**
Spring_07 ~ Spring_08	-10.05	-6.61	-12.056	**3.168e-05**	0	**0.003538**
Spring_07 ~ Spring_09	1.17	0.17	4.2426	**0.001709**	33.5	**0.007526**
Spring_08 ~ Spring_09	9.5	0.17	13.5028	**1.708e-05**	36	**0.003538**
Summer_06 ~ Summer_07	46.5	31.0	1.8808	0.1159	13.5	0.1465
Summer_06 ~ Summer_ 08	46.5	53.0	-0.3937	0.713	7	0.8857
Summer_06 ~ Summer _09	46.50	27.25	2.3178	0.06506	15	0.05714
Summer_07 ~ Summer 08	31	53	-1.3998	0.2425	5	0.4857
Summer_07 ~ Summer 09	31.00	27.25	0.5693	0.5899	10.5	0.5614
Summer_08 ~ Summer 09	53.00	27.25	1.6349	0.1856	12	0.3429
Fall_06 ~ Fall_07	12.75	36.50	-10.30	**0.0009584**	0	**0.02857**
Fall_06 ~ Fall_08	12.75	28.25	-5.6756	**0.001765**	0	**0.0294**
Fall_06 ~ Fall_09	12.75	0.50	5.4002	**0.009647**	16	**0.02652**
Fall_07 ~ Fall_08	36.50	28.25	4.7798	**0.009052**	16	**0.0294**
Fall_07 ~ Fall_09	36.5	0.5	44.0908	**2.192e-08**	16	**0.02652**
Fall_08 ~ Fall_09	28.25	0.50	16.5469	**0.0001642**	16	**0.02558**

Kolmgorov-Smirnov, F, and Kruskal-Wallis tests for significant differences in distribution and variance of interannual precipitation (mm).

Season	**Kolmogorov-Smirnov**		**F-test**		**Kruskal-Wallis**	
	D	**p-value**	**F**	**p-value**	**chi-squared**	**p-value**
		(α=0.05)		(α=0.05)		(α=0.05)
Winter06_07 ~ Winter07_08	1	**0.00496**	0.054	**0.0061**	8.64	**0.003289**
Winter06_07 ~ Winter08_09	1	**0.00496**	0.013	**0.0002**	8.64	**0.003289**
Winter06_07 ~ Winter09_10	1	**0.00496**	0.012	**0.0002**	8.64	**0.003289**
Winter07_08 ~ Winter08_09	0.83	**0.03101**	0.248	0.1523	4.3638	**0.03671**
Winter07_08 ~ Winter09_10	1	**0.00496**	0.236	0.1398	8.3662	**0.003823**
Winter08_09 ~ Winter09_10	1	**0.00496**	0.954	0.9601	8.3662	**0.003823**
Spring_07 ~ Spring_08	1	**0.00496**	0.062	**0.0083**	9	**0.0027**
Spring_07 ~ Spring_09	0.83	**0.03101**	1	1	7.627	**0.00575**
Spring_08 ~ Spring_09	1	**0.00496**	16.2	**0.0083**	9	**0.0027**
Summer_06 ~ Summer_07	0.75	0.2106	2.209	0.532	2.5512	0.1102
Summer_06 ~ Summer_ 08	0.5	0.7714	0.207	0.2283	0.0833	0.7728
Summer_06 ~ Summer _09	0.75	0.2286	2.103	0.5571	4.0833	**0.04331**
Summer_07 ~ Summer 08	0.5	0.7714	0.094	0.0829	0.75	0.3865
Summer_07 ~ Summer 09	0.5	0.6994	0.952	0.9688	0.5271	0.4678
Summer_08 ~ Summer 09	0.5	0.7714	10.16	0.0885	1.3333	0.2482
Fall_06 ~ Fall_07	1	**0.02857**	11.75	0.0728	5.3333	**0.02092**
Fall_06 ~ Fall_08	1	**0.03663**	1.910	0.6083	5.3976	**0.02016**
Fall_06 ~ Fall_09	1	**0.03663**	19.58	**0.0358**	5.6	**0.01796**
Fall_07 ~ Fall_08	1	**0.03663**	0.162	0.1699	5.3976	**0.02016**
Fall_07 ~ Fall_09	1	**0.03663**	1.666	0.685	5.6	**0.01796**
Fall_08 ~ Fall_09	1	**0.03663**	10.25	0.0875	5.6709	**0.01725**

Student's t and Mann-Whitney tests for intrannual variation in precipitation means (mm).

Station	Mean1	Mean2	*t*	p-value	W	p-value
Winter 2006/2007 ~ Spring 2007	2.2	1.2	1.8898	0.1141	20.5	0.08326
Winter 2006/2007 ~ Summer 2007	2.2	38.6	-11.128	**0.0002901**	0	**0.01116**
Winter 2006/2007 ~ Fall 2007	2.2	36.6	-48.649	**3.637e-11**	0	**0.01091**
Spring 2007 ~ Summer 2007	1.2	38.6	-11.542	**0.0003085**	0	**0.0097**
Spring 2007 ~ Fall 2007	1.2	36.6	-64.631	**9.254e-09**	0	**0.009467**
Summer 2007 ~ Fall 2007	38.6	36.6	0.6108	0.5728	16.5	0.462
Winter 2007/2008 ~ Spring 2008	19.33	9.5	5.3112	**0.001422**	36	**0.004847**
Winter 2007/2008 ~ Summer 2008	19.33	43.5	-2.1177	0.08528	3	**0.01916**
Winter 2007/2008~ Fall 2008	19.33	32.33	-3.9763	**0.003736**	0	**0.004922**
Spring 2008 ~ Summer 2008	9.5	43.5	-3.0087	**0.02954**	0	**0.004847**
Spring 2008 ~ Fall 2008	9.5	32.33	-7.9927	**0.0002928**	0	**0.004847**
Summer 2008 ~ Fall 2008	43.5	32.33	0.9612	0.3761	19	0.936
Winter 2008/2009 ~ Spring 2009	35	0.167	10.0439	**0.0001631**	36	**0.003601**
Winter 2008/2009 ~ Summer 2009	35	26	1.9044	0.08615	26.5	0.1986
Winter 2008/2009~ Fall 2009	35	0.33	9.9614	**0.0001569**	36	**0.003601**
Spring 2009 ~ Summer 2009	0.167	26	-8.0256	**0.0004735**	0	**0.003665**
Spring 2009 ~ Fall 2009	0.167	0.33	-0.4472	0.6676	17.5	1
Summer 2009~ Fall 2009	26	0.33	7.9419	**0.000462**	36	**0.003665**

Kolmgorov-Smirnov, F, and Kruskal-Wallis tests for intrannual differences in precipitation variance (mm).

	Kolmgorov-Smirnov		**F-test**		**Kruskal-Wallis**	
Station	**D**	**p-value**	**F**	**p-value**	**Chi-squared**	**p-value**
Winter 2006/2007 ~ Spring 2007	0.6	0.3291	6	0.1108	2.5	0.1138
Winter 2006/2007 ~ Summer 2007	1	**0.01348**	0.0229	**0.002973**	4	0.406
Winter 2006/2007 ~ Fall 2007	1	**0.01348**	0.9231	0.94	3	0.3916
Spring 2007 ~ Summer 2007	1	**0.01348**	0.0038	**8.685e-05**	4	0.406
Spring 2007 ~ Fall 2007	1	**0.01348**	0.1538	**0.09719**	1.5	0.6823
Summer 2007 ~ Fall 2007	0.6	0.3291	40.2308	**0.003472**	3.2	0.3618
Winter 2007/2008 ~ Spring 2008	1	**0.004958**	6.6173	0.05855	4.5221	0.2103
Winter 2007/2008 ~ Summer 2008	0.6667	0.1389	0.0234	**0.000838**	1.3235	0.8574
Winter 2007/2008~ Fall 2008	1	**0.004958**	0.3862	0.3197	4.8529	0.3027
Spring 2008 ~ Summer 2008	1	**0.004958**	0.3862	0.3197	4.3939	0.3553
Spring 2008 ~ Fall 2008	1	**0.004958**	0.0584	**0.007304**	1.9318	0.7483
Summer 2008 ~ Fall 2008	0.3333	0.8928	16.5022	**0.007965**	4.4118	0.3531
Winter 2008/2009 ~ Spring 2009	1	**0.004958**	432	**2.778e-06**	0.7941	0.3729
Winter 2008/2009 ~ Summer 2009	0.6667	0.1389	1.1613	0.8737	5	0.4159
Winter 2008/2009 ~ Fall 2009	1	**0.004958**	108	**8.673e-05**	2.2059	0.1375
Spring 2009 ~ Summer 2009	1	**0.004958**	0.0027	**4.032e-06**	5	0.4159
Spring 2009 ~ Fall 2009	0.1667	1	0.25	0.1544	0.2	0.6547
Summer 2009~ Fall 2009	1	**0.004958**	93	**0.0001254**	2.1429	0.1432